TFAWS Active Thermal Paper Session

Thermal Design Challenges Posed by the Four Bed CO2 Scrubber COTS Air-Save Pump

Dan Popok
Marshall Space Flight Center,
Linc Research | Jacobs Space Exploration Group (JSEG)
Engineering Services and Science
Capabilities Augmentation (ESSCA)
dan.popok@nasa.gov

Presented By
Dan Popok

Thermal & Fluids Analysis Workshop
TFAWS 2020
August 18-20, 2020
Virtual Conference

Introduction

- The Four Bed Carbon Dioxide (**4BCO2**) scrubber Air-Save Pump (**ASP**) operates as part of the adsorbent bed regeneration cycle.
- ASP removes residual air from the bed for return to the cabin prior to heat and vacuum exposure which removes the CO2, regenerating the bed.
- 4BCO2 employs a Commercial Off-the-Shelf (**COTS**) scroll type air pump
  - Repackaged in an acoustically insulated enclosure to reduce noise
  - Mounted to a cold plate.
- The International Space Station (**ISS**) Low Temperature Loop (**LTL**), operates between 38F and 50F
  - Flows first through a precooler to cool the process air. Precooler performance requires LTL.
  - Then flows through the cold plate, cooling the pump. Acoustic enclosure precludes air cooling, requiring LTL.
- Results in competing ASP thermal design goals:
  - Keep the pump and motor sufficiently cool
  - Avoid forming condensation due to over-cooling.
- Surfaces below 60F typically warrant careful consideration of condensation.
- A test-calibrated thermal model demonstrates such a balanced design is feasible with temperatures above 60F.
- A separate, coupled fluid model predicts the potential for condensation formation, allowing risk assessment of flying with the unmodified design.

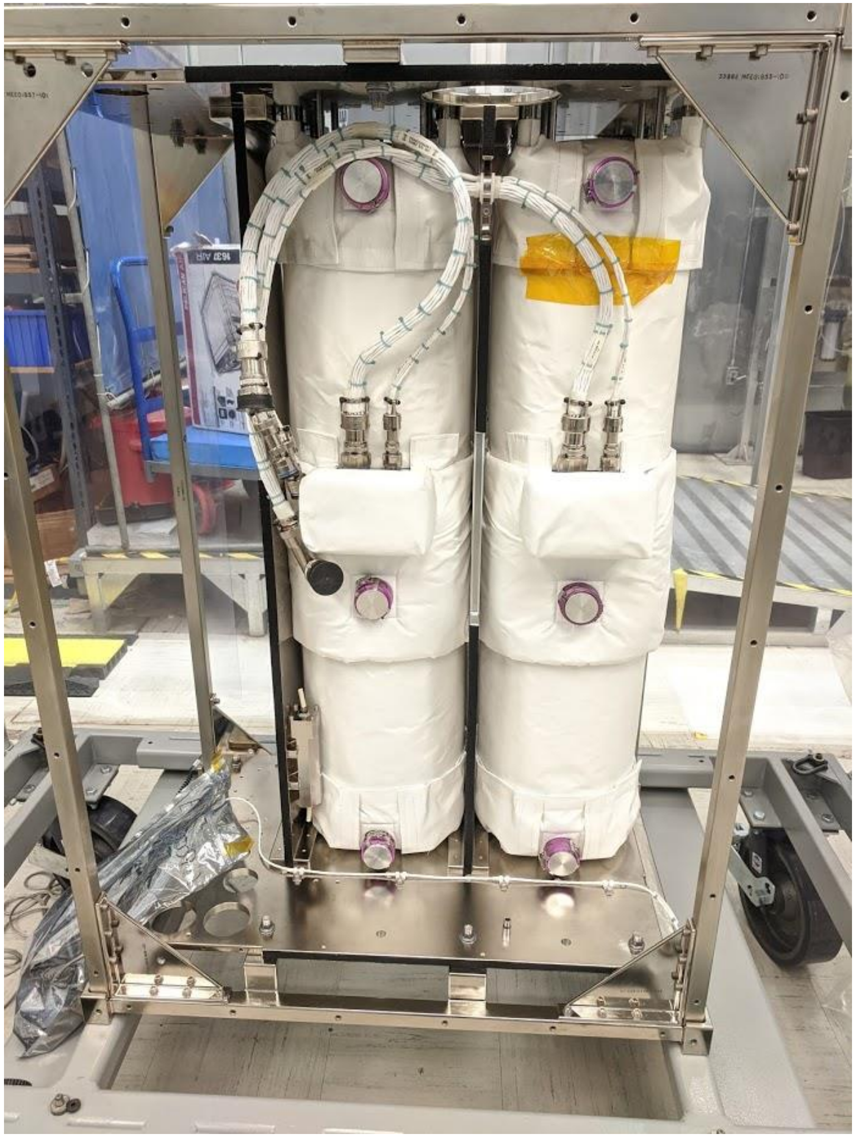
Outline

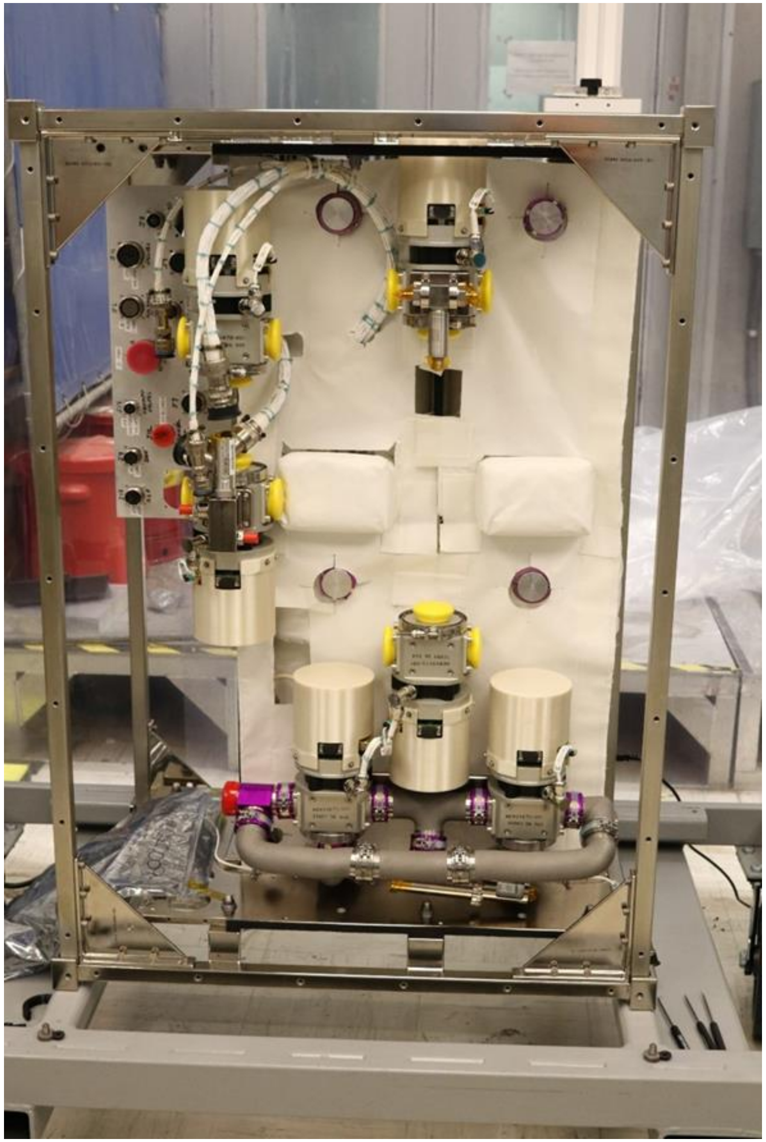
- 4BCO2 description
- The COTS air pump
- Thermal characterization testing showing condensation risk
- Test correlated thermal model
- Condensation eliminating design mods
- Condensation model and analysis
- Questions?

4BCO2 Description

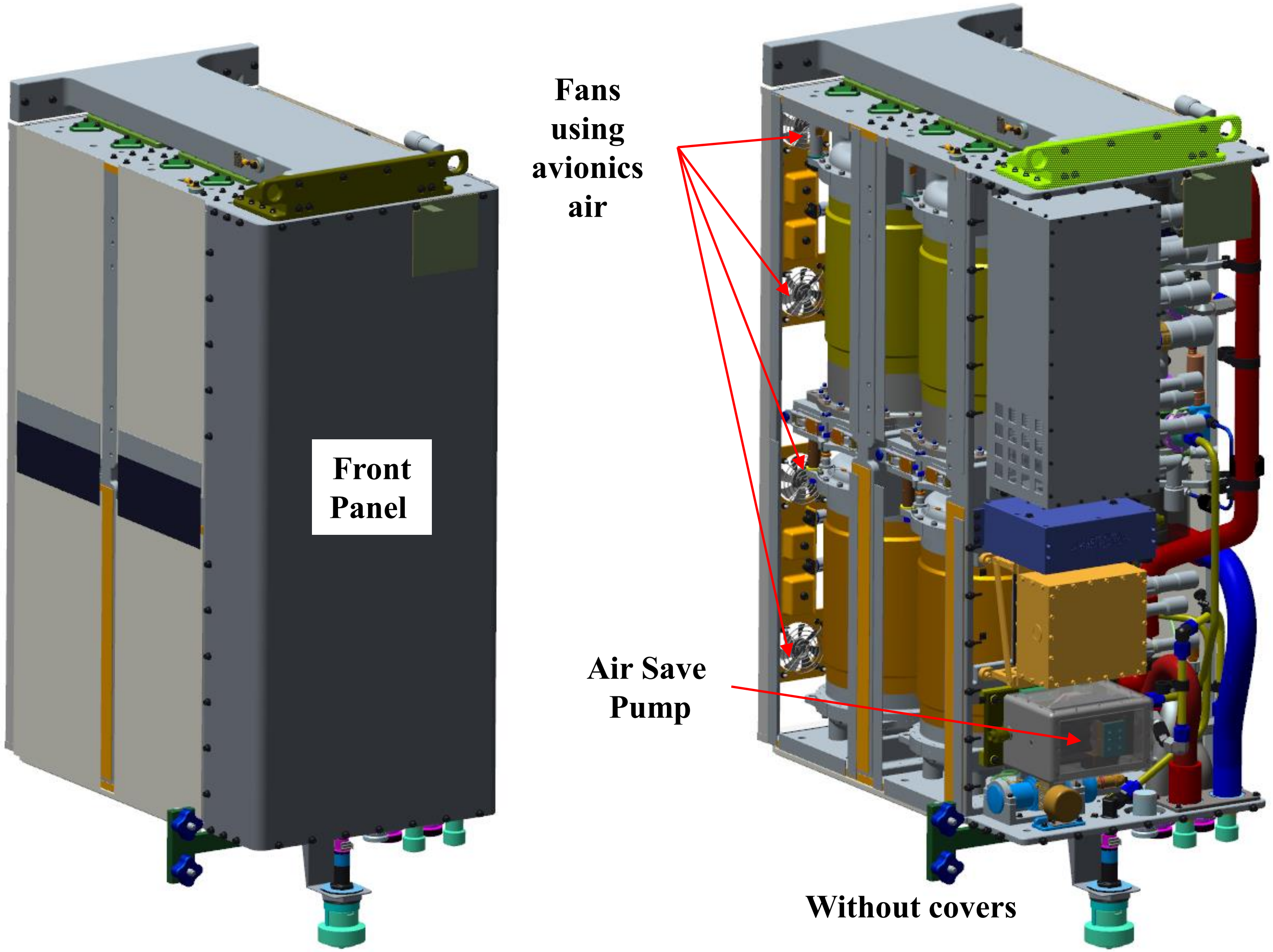
- CO2 scrubber for EXPRESS Rack
- Consists of 4 beds
  - Two CO2 adsorbing beds
  - Two desiccant beds
- Fluid interfaces
  - Avionics air cooling: 18.3C (65F) to 29.4C (85F)
  - LTL cooling: 3.3C (38F) to 10C (50F)
  - Process air: CO2 removed and returned to cabin
  - Vacuum port: disposes extracted CO2
- LTL
  - Cools process air upstream of adsorbent bed
  - Cools the air save pump

Flight Hardware Assembly

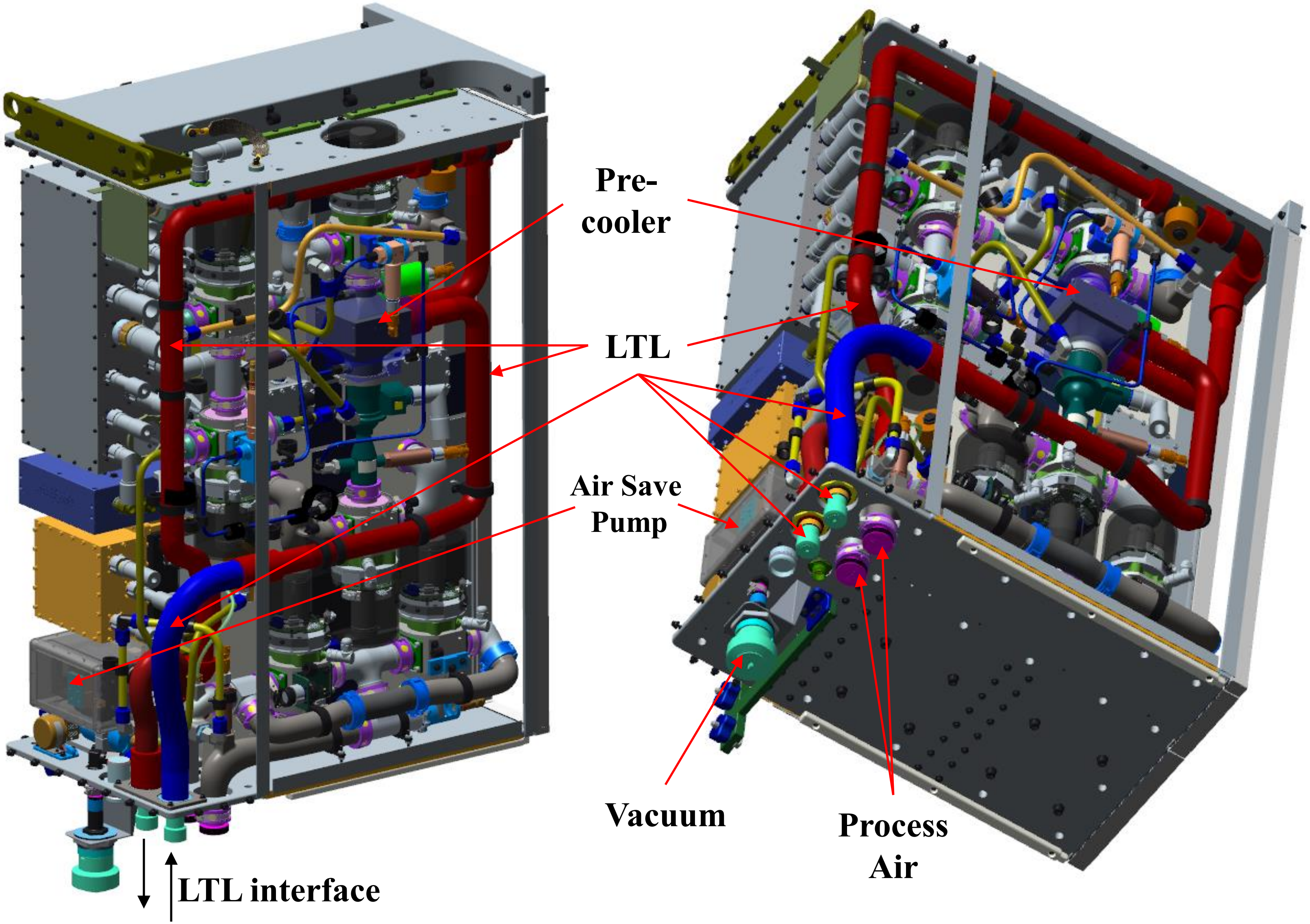




4BCO2


Fans using avionics air
Front Panel
Air Save Pump
Without covers

4BCO2



Pre-
cooler
LTL
Air Save
Pump
Vacuum
Process
Air
LTL interface

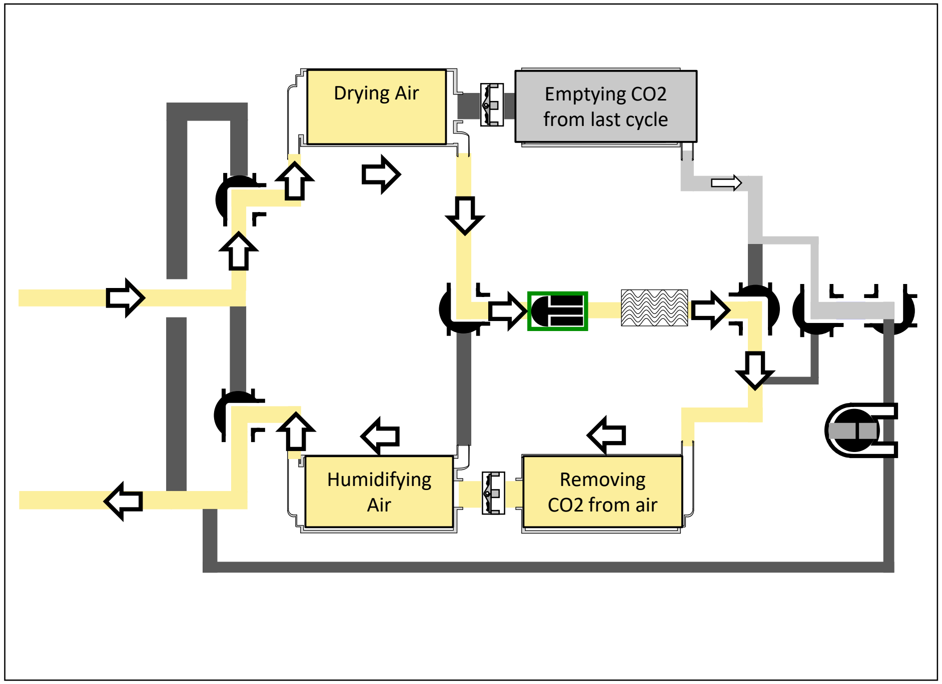
ASP Purpose

- 4BCO2 operates in two 80 minute half cycles –
  – One adsorbent bed scrubs CO2 while the other regenerates
  – One desiccant bed dries incoming ISS cabin air while the other re-humidifies air going back to the cabin
- ASP participates in adsorbent bed regeneration process
  – For the first 10 minutes: pumps residual air from the adsorbent bed for return to the cabin
  – For the remaining 70 minutes: heaters and vacuum exposure removes CO2, recharging the bed for the next half cycle

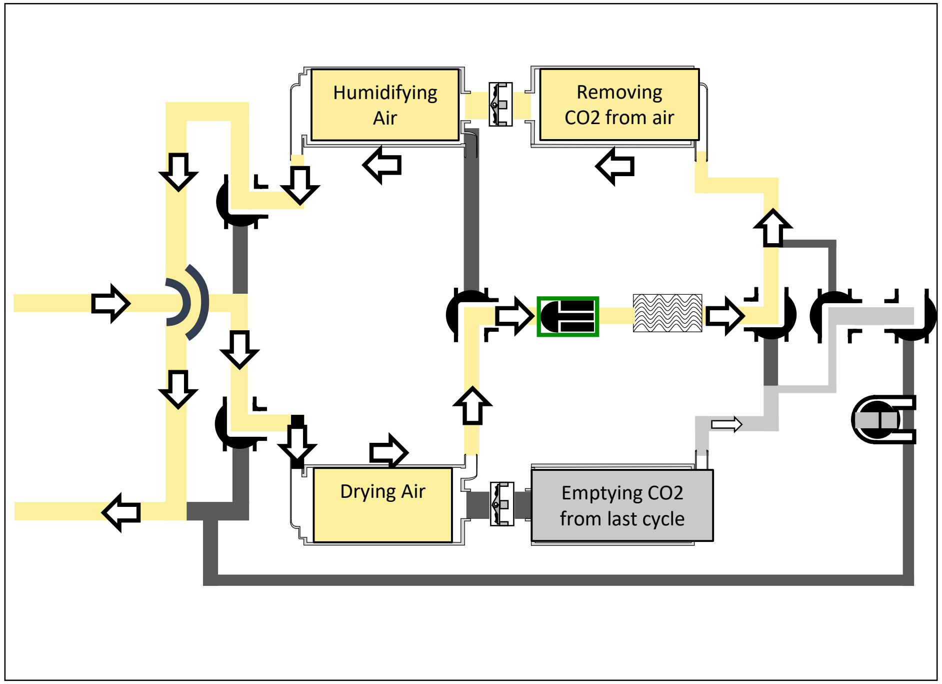
4BCO2 Operation

Description of Cycle and Half-Cycle

One Cycle



Half Cycle A

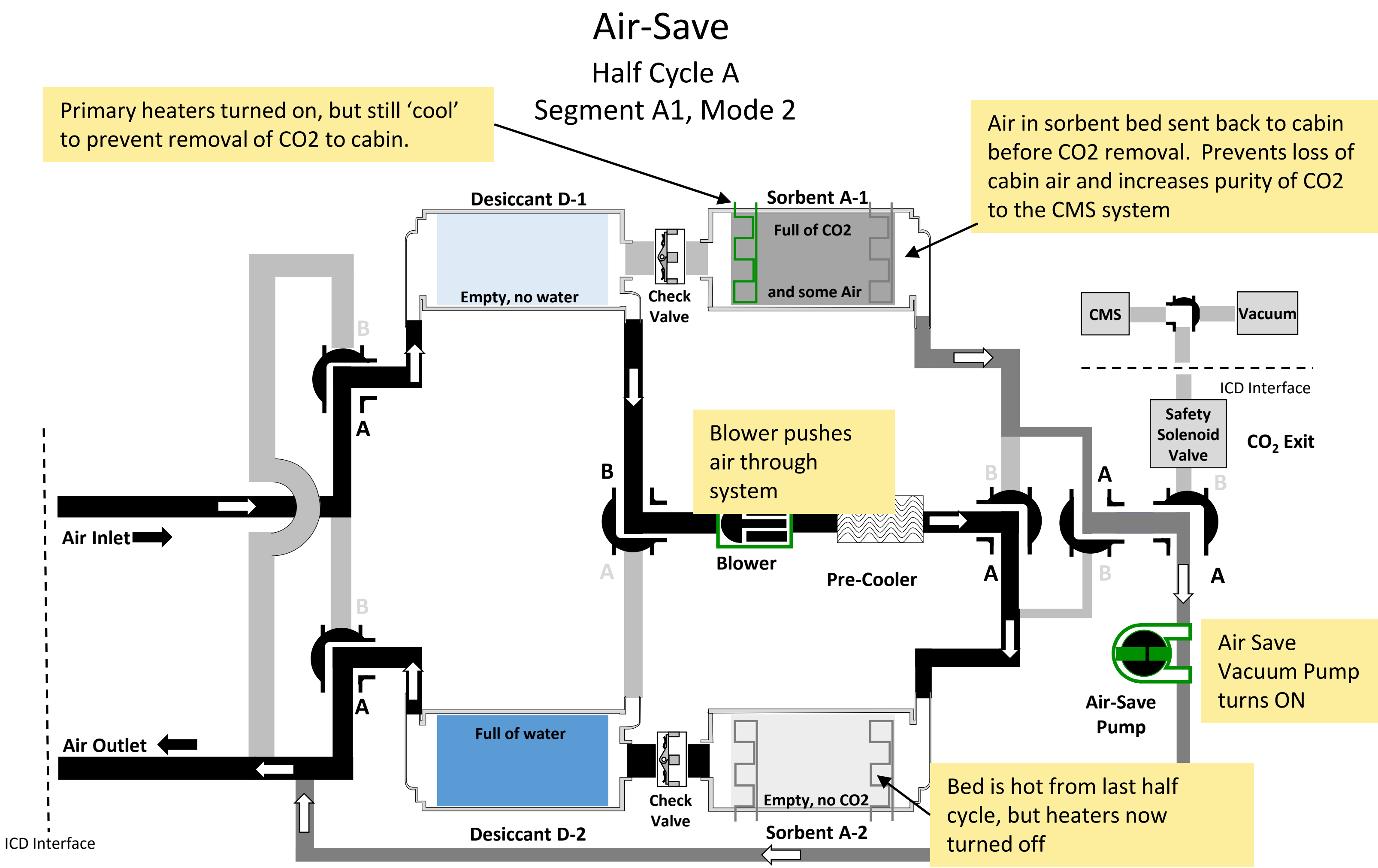


Half Cycle B

4BCO2 Operation

- Flipping through the next 25 slides fairly rapidly to show 4BCO2 operation as “pseudo animation”

4BCO2 Operation (1)

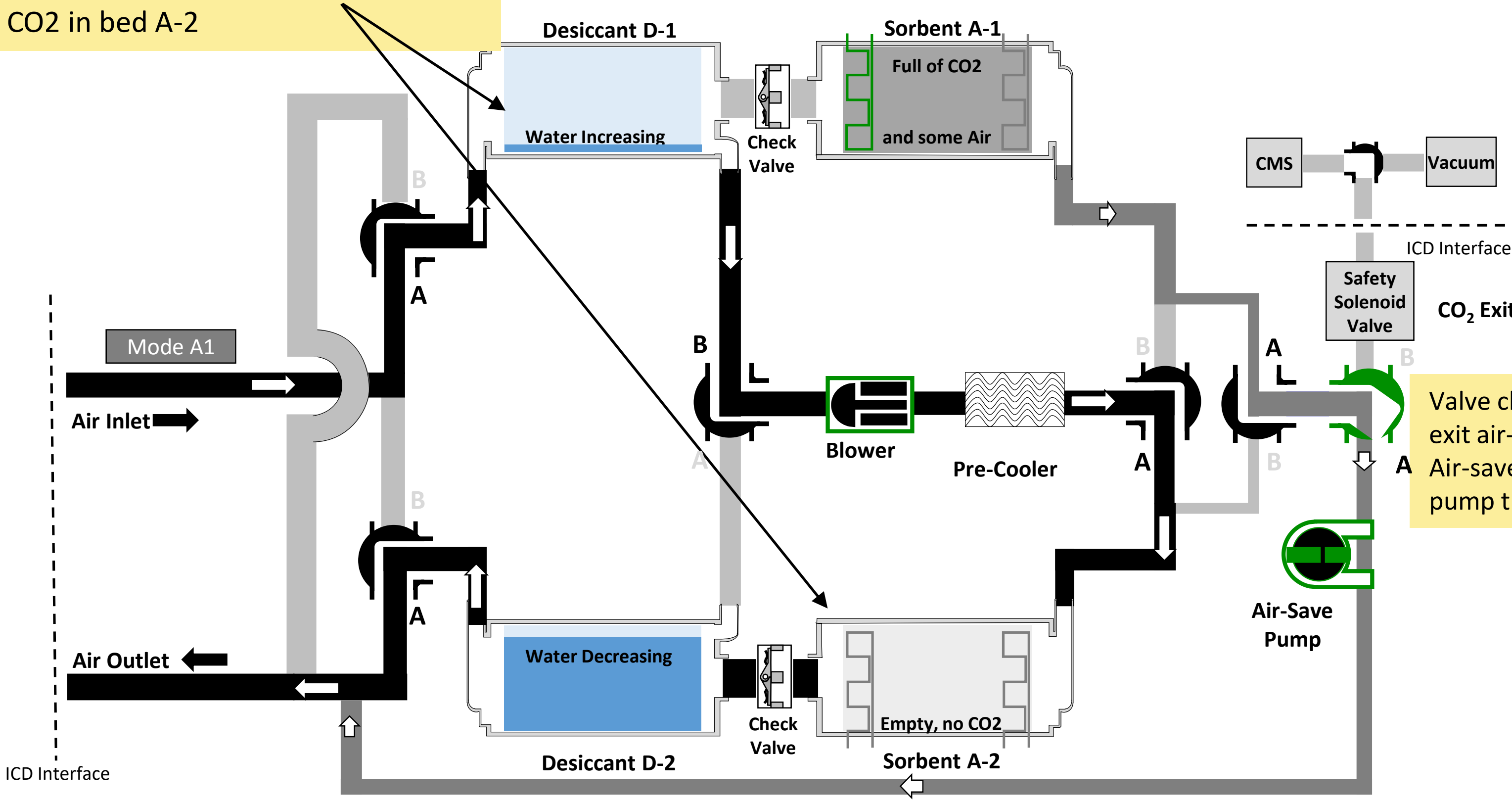


4BCO2 Operation (2)

Transition out of Air-Save

Half Cycle A
Segment A1, Mode 2

Desiccant bed removes moisture from incoming air. Moisture in the Sorbent bed limits adsorption of CO2 in bed A-2

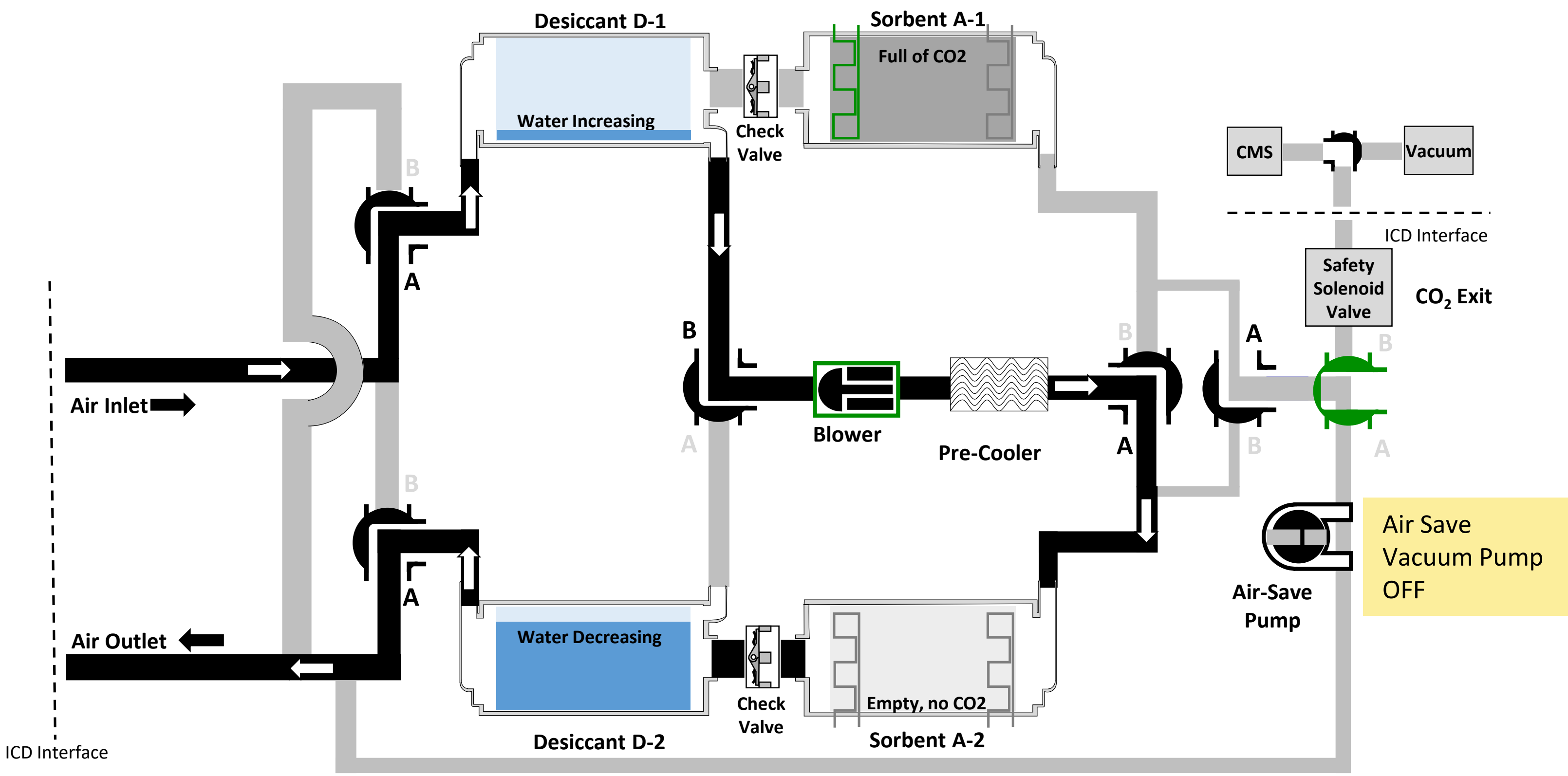


Valve changes as we exit air-save mode. Air-save vacuum pump turns off.

4BCO2 Operation (3)

Transition out of Air-Save

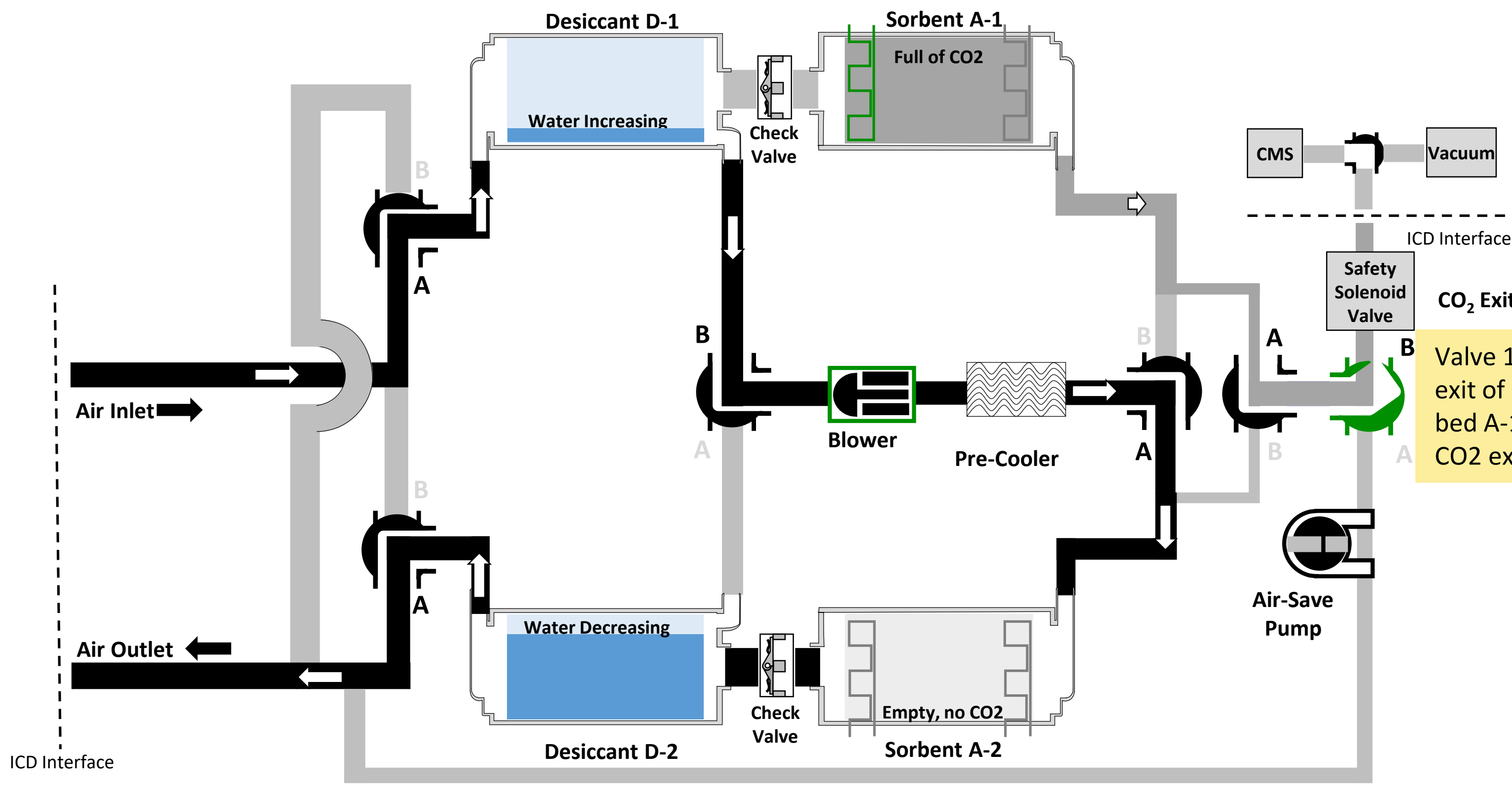
Half Cycle A
Segment A1, Mode 2



Transition out of Air-Save

Half Cycle A

Segment A1, Mode 2



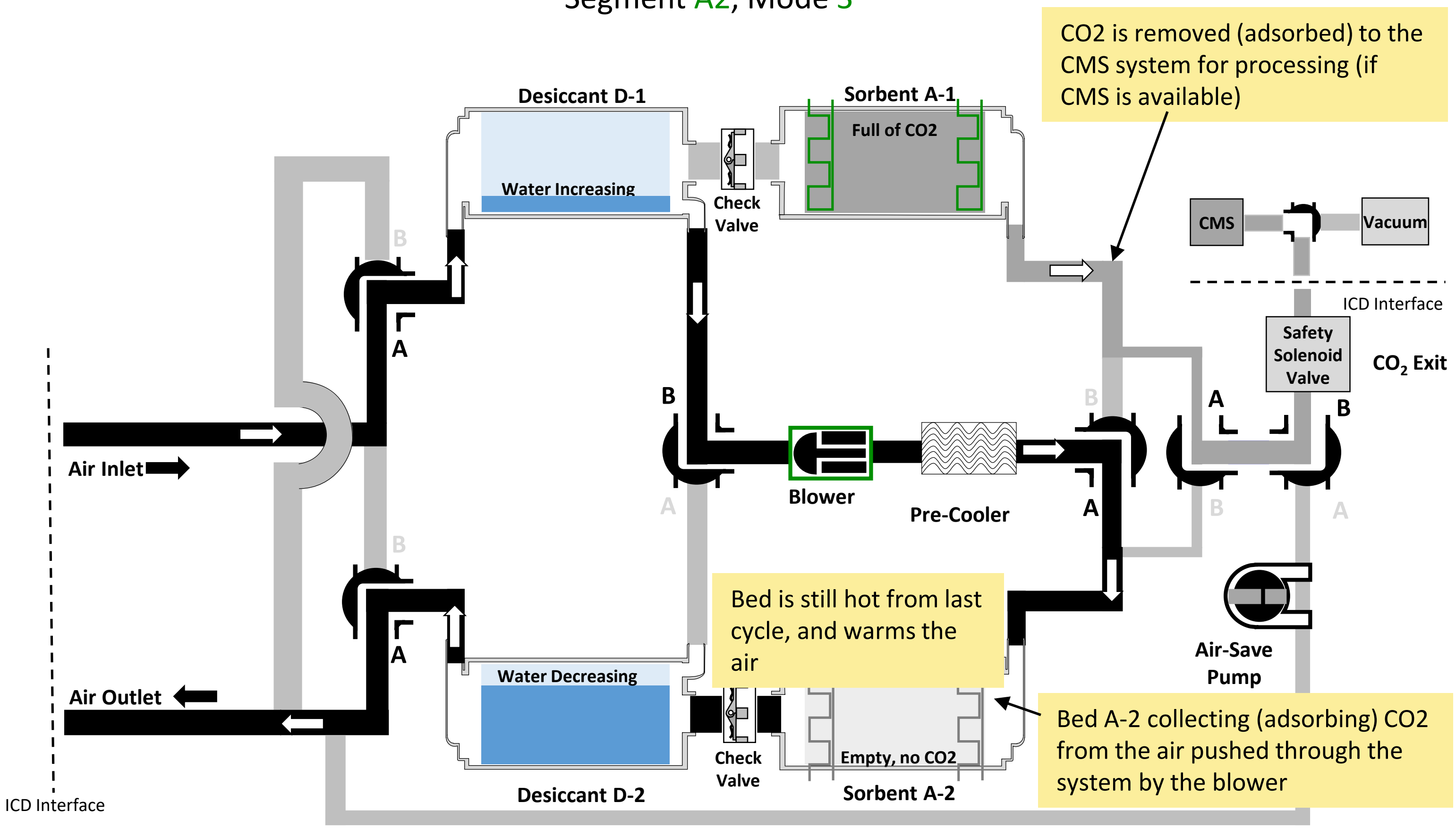
Valve 106 directs exit of Sorbent bed A-1 to the CO2 exit

4BCO2 Operation (5)

Adsorption of Bed A-2: Desorption of Bed A-1

Half Cycle A

Segment A2, Mode 3

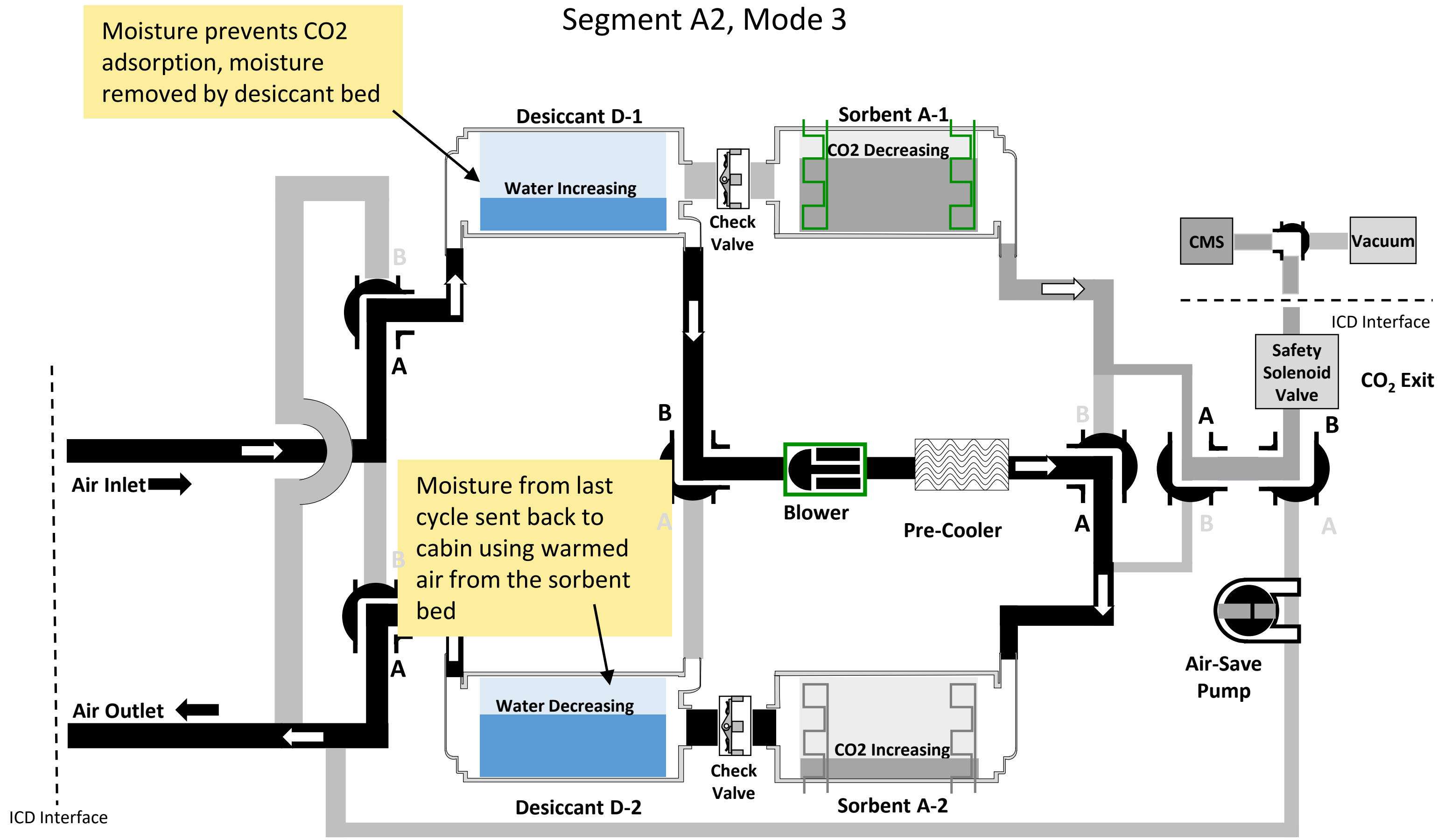


4BCO2 Operation (6)

Adsorption of Bed A-2: Desorption of Bed A-1

Half Cycle A

Segment A2, Mode 3

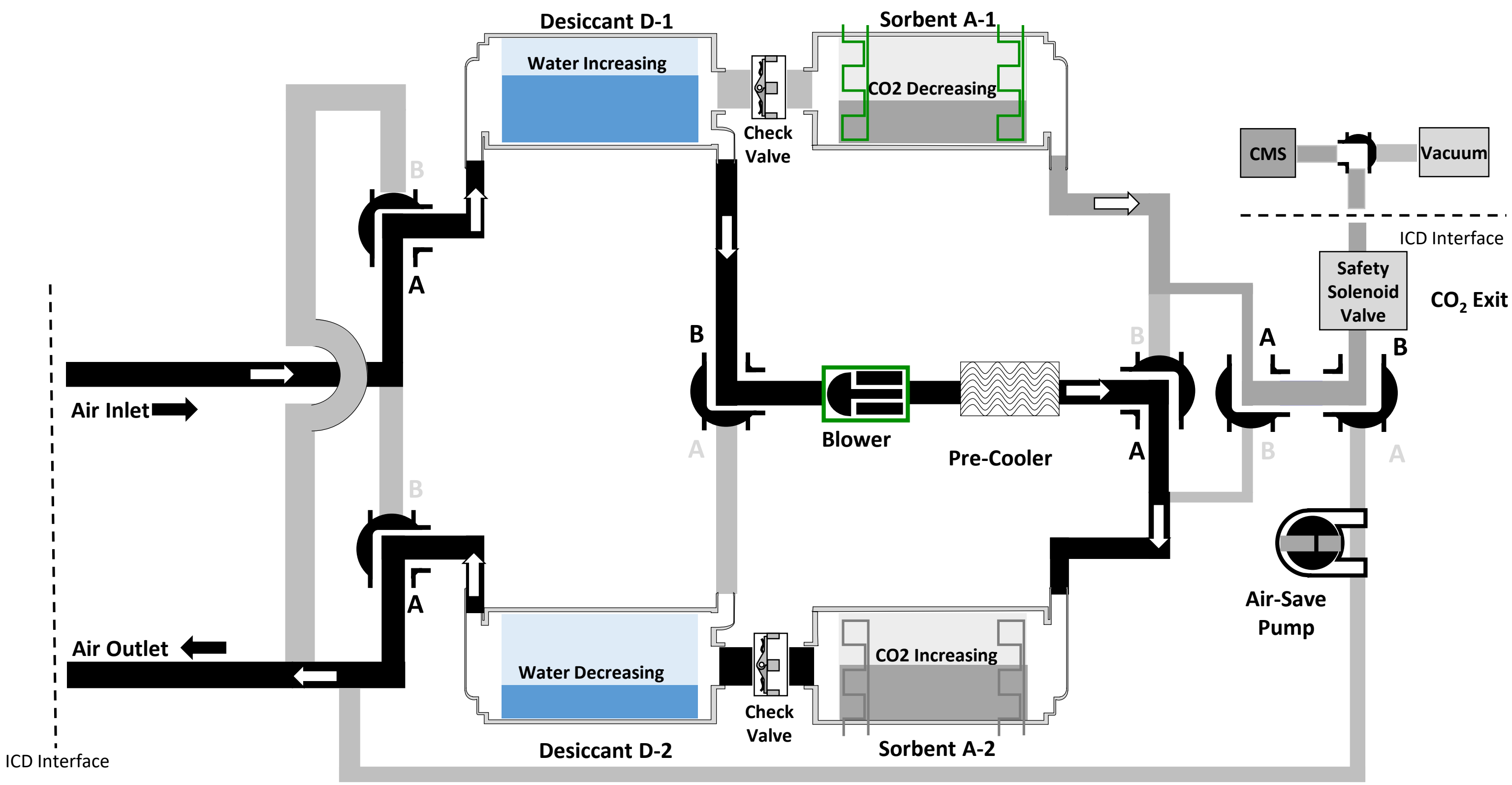


4BCO2 Operation (7)

Adsorption of Bed A-2: Desorption of Bed A-1

Half Cycle A

Segment A2, Mode 3

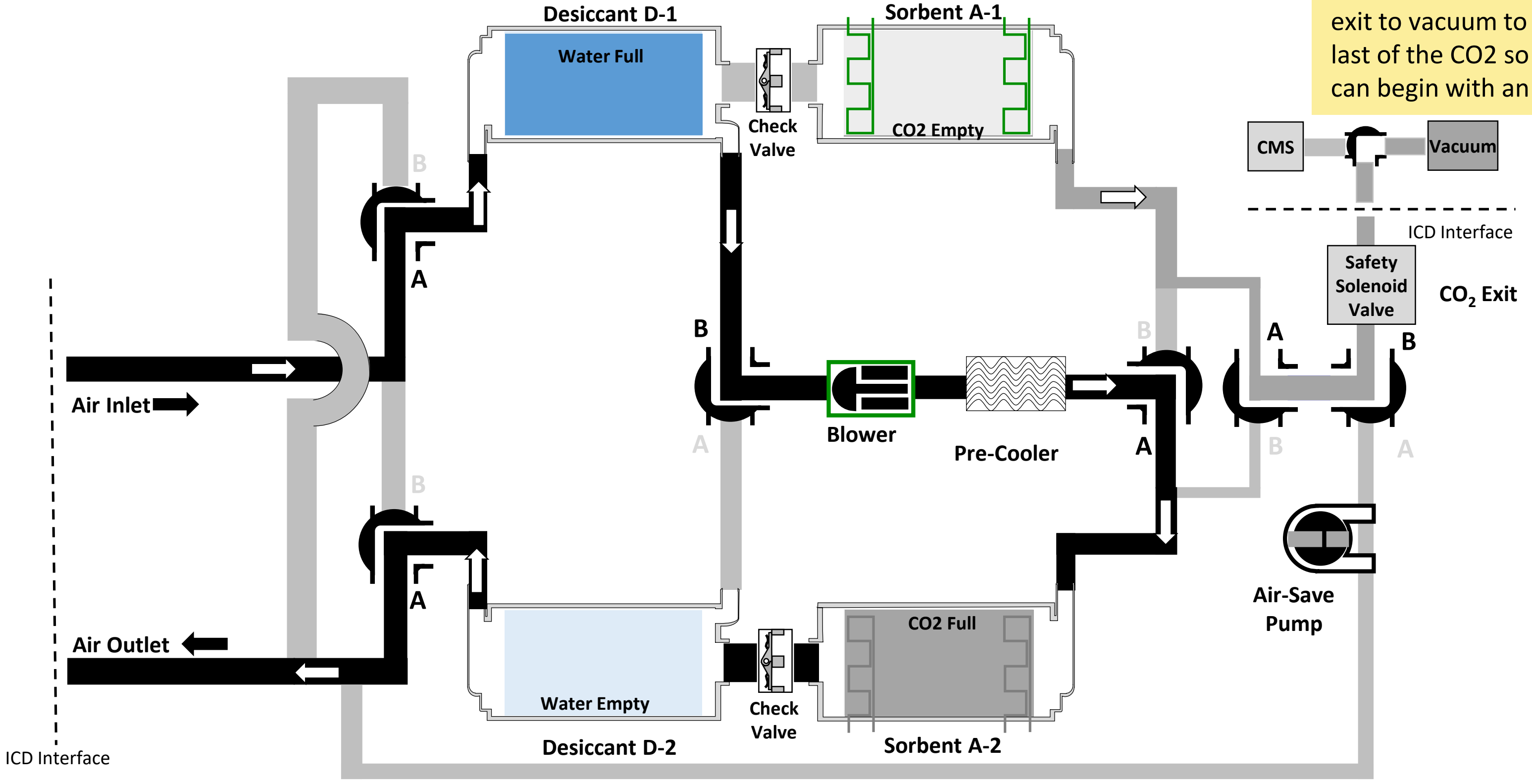


Last Segment (CO2 to Vacuum)

Half Cycle A

Segment A3, Mode 4

Non-4BMS valve connects CO2 exit to vacuum to remove the last of the CO2 so next cycle can begin with an 'empty' bed.

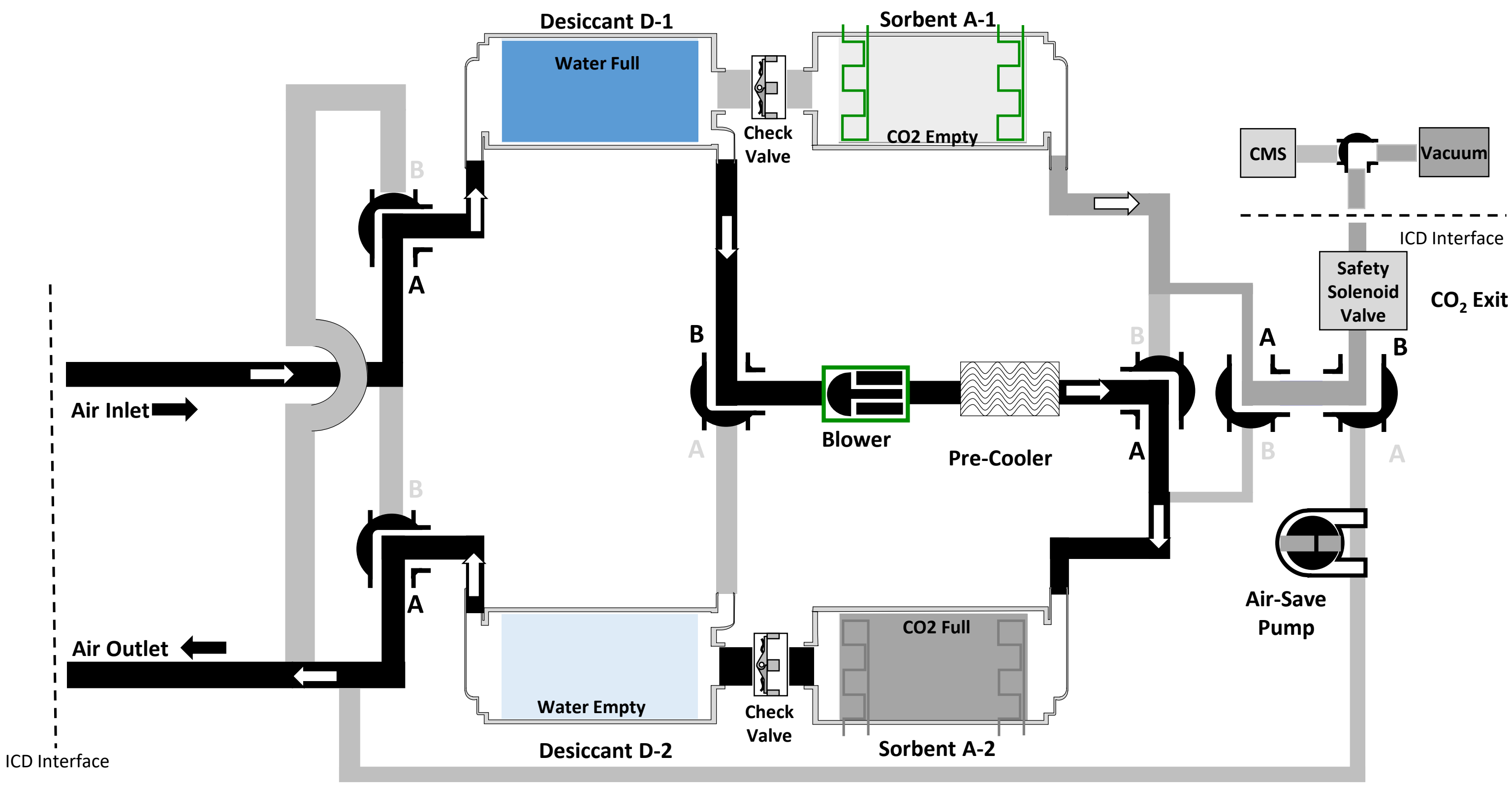


4BCO2 Operation (9)

End of First Half Cycle

Half Cycle A

Segment A3, Mode 4



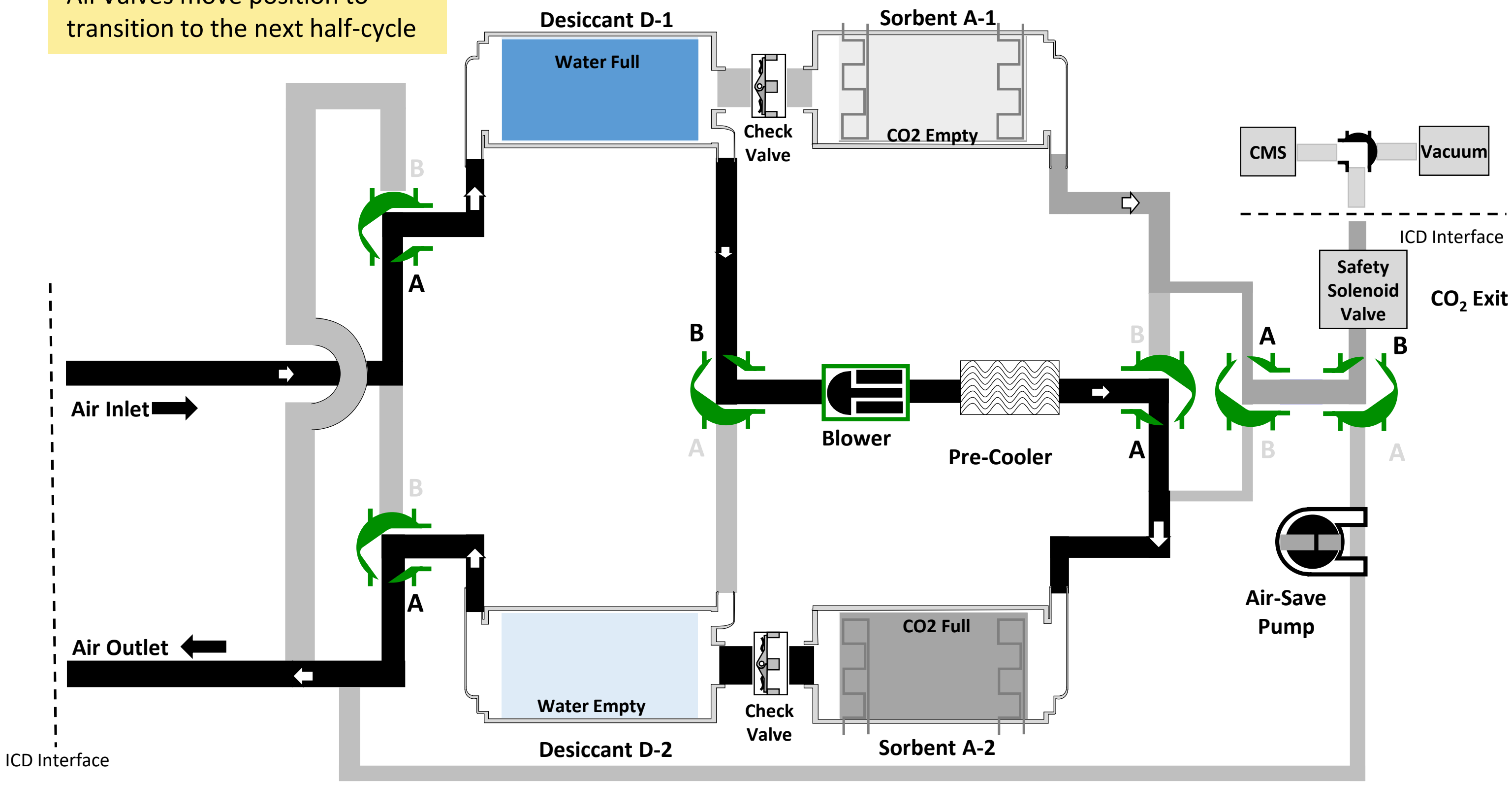
4BCO2 Operation (10)

Transition to Second Half Cycle Air-Save

Half Cycle A

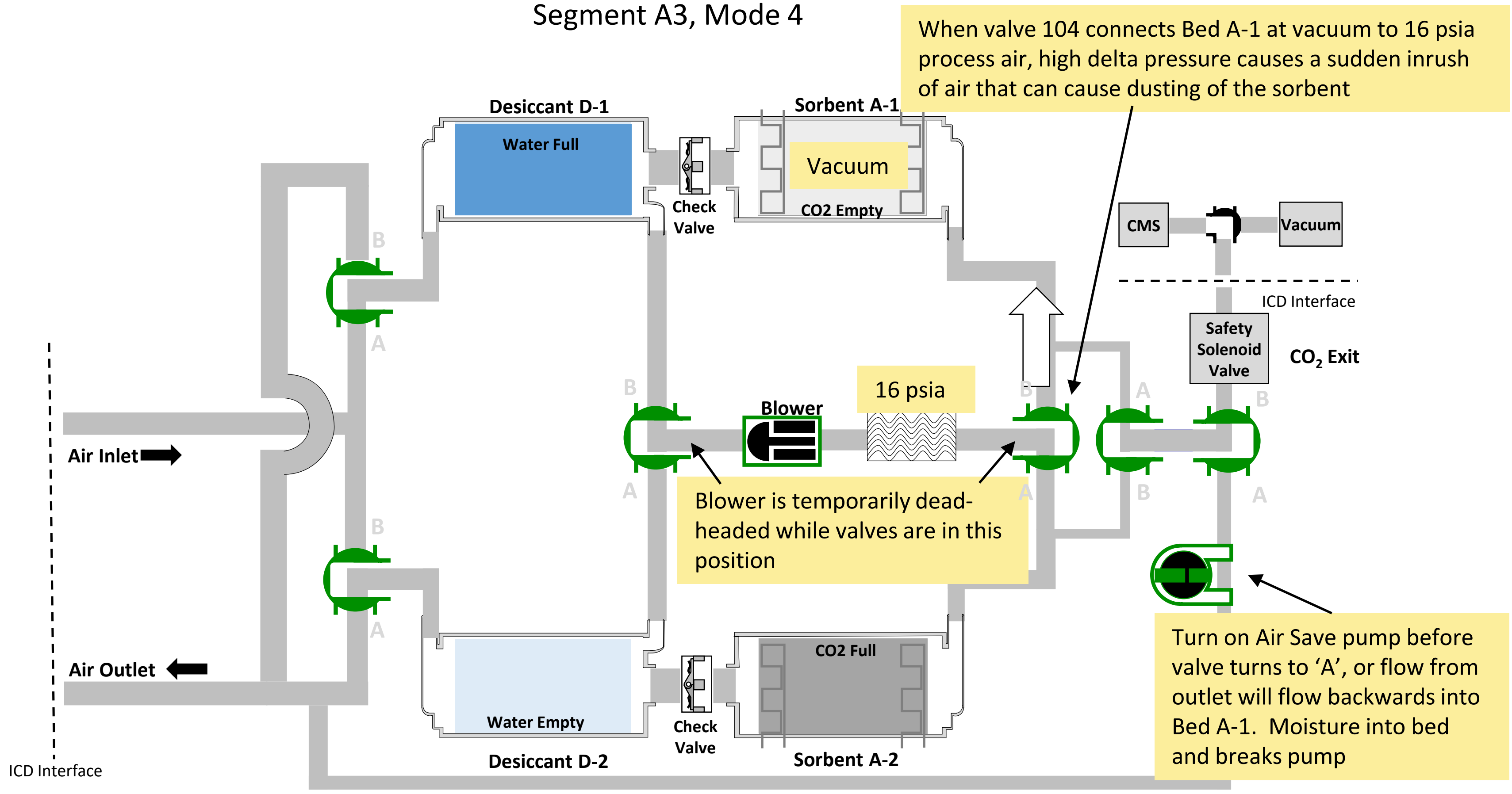
Segment A3, Mode 4

All Valves move position to transition to the next half-cycle



Transition to Second Half Cycle Air-Save

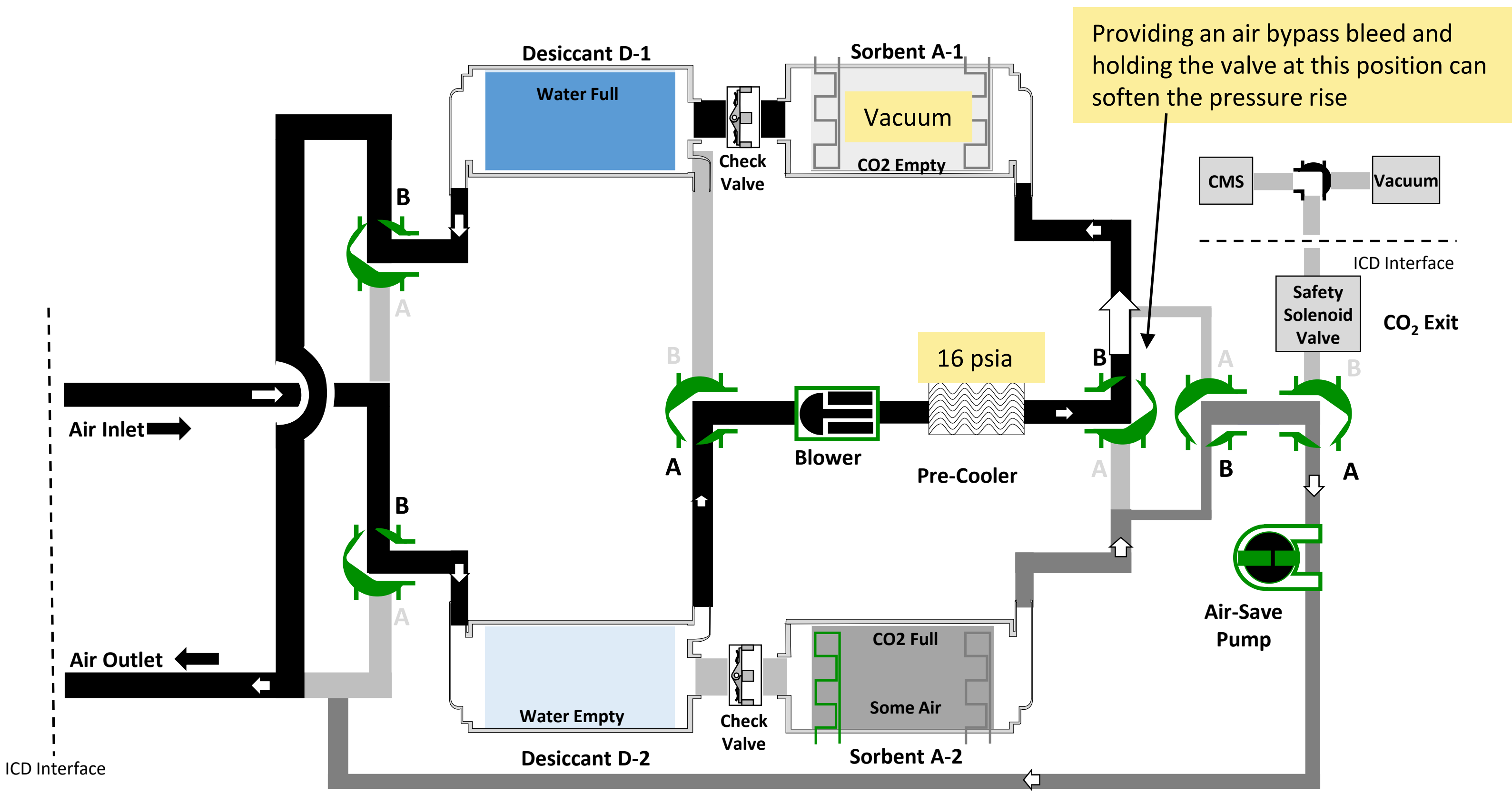
Temporary Cessation of All Air Flow
Segment A3, Mode 4



Transition to Second Half Cycle Air-Save

Half Cycle A

Segment A3, Mode 4

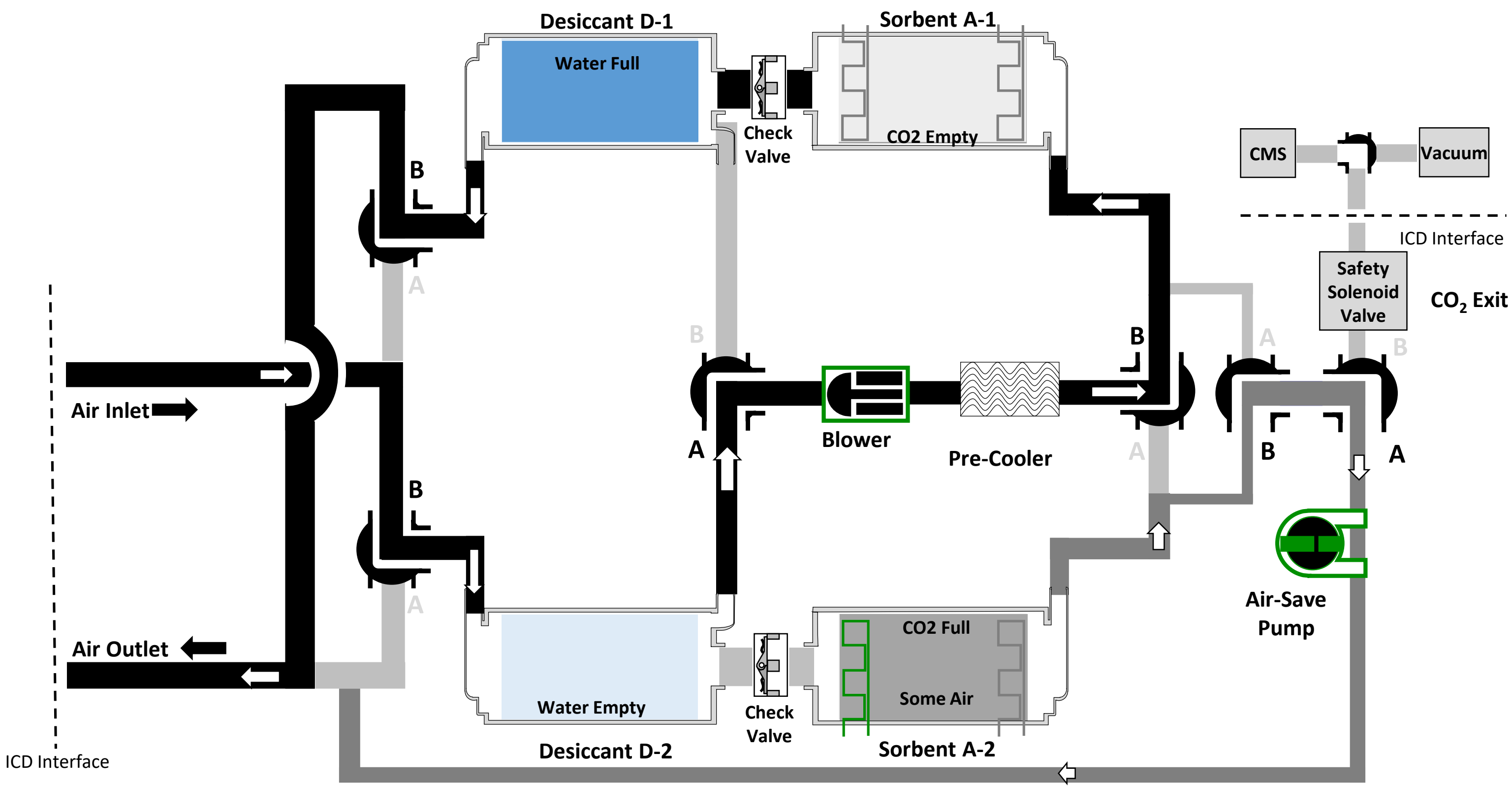


Second Half Cycle Air-Save

Half Cycle B

Segment B1, Mode 5

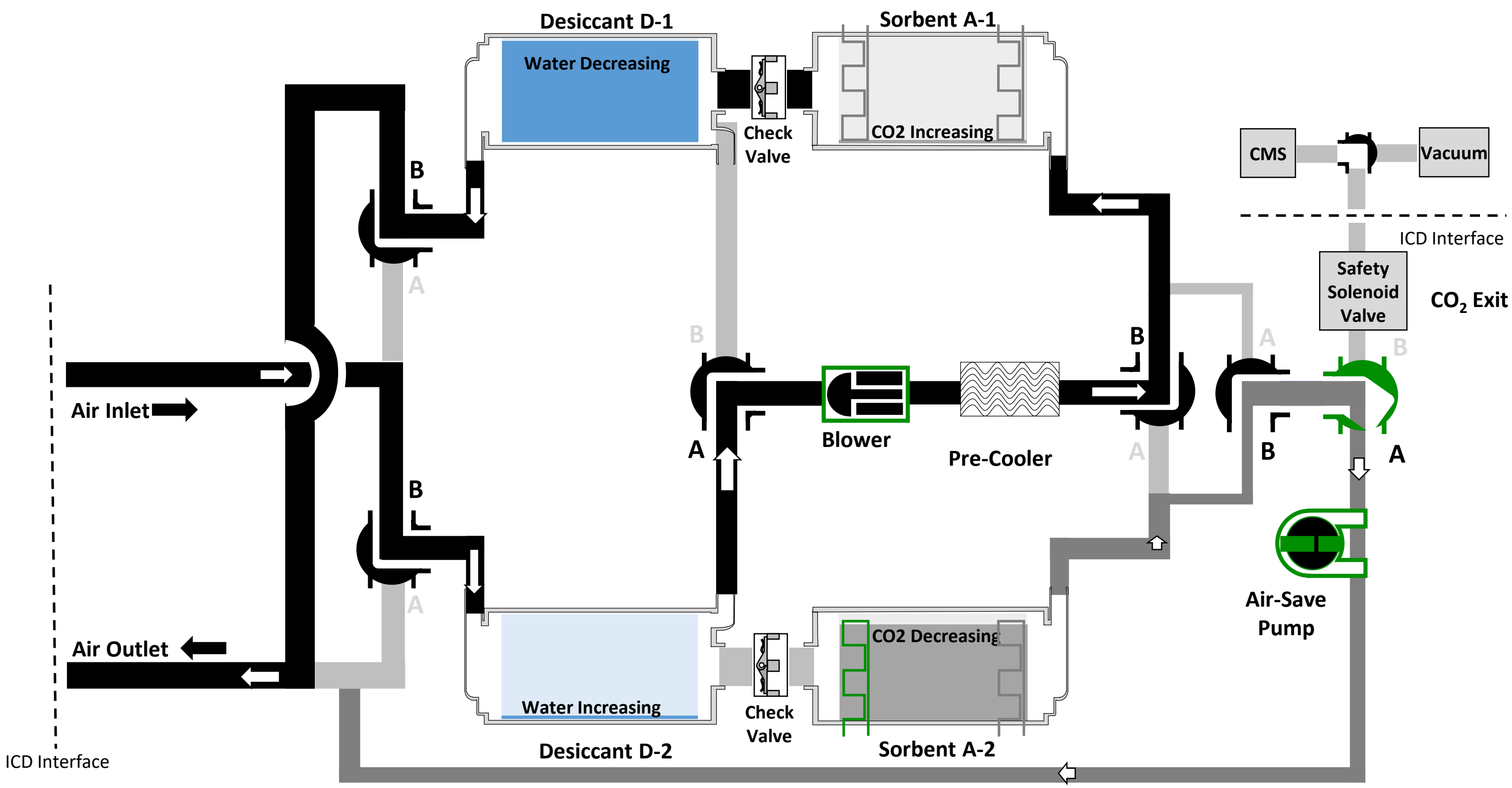
Half Cycle is now repeated, but in the opposite direction



4BCO2 Operation (14)

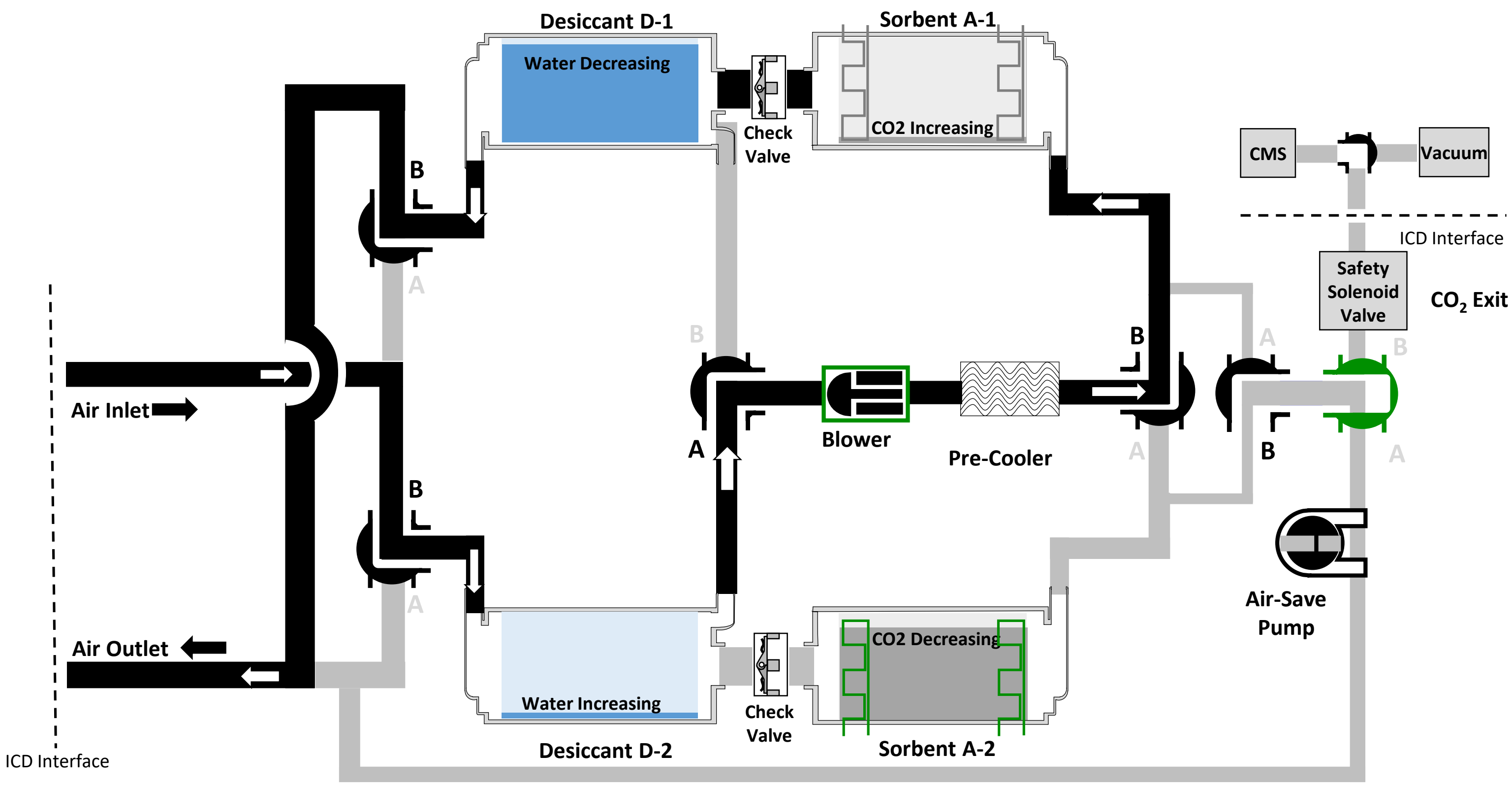
Transition out of Second Half Cycle Air-Save

Half Cycle B
Segment B1, Mode 5



Transition out of Second Half Cycle Air-Save

Half Cycle B
Segment B1, Mode 5

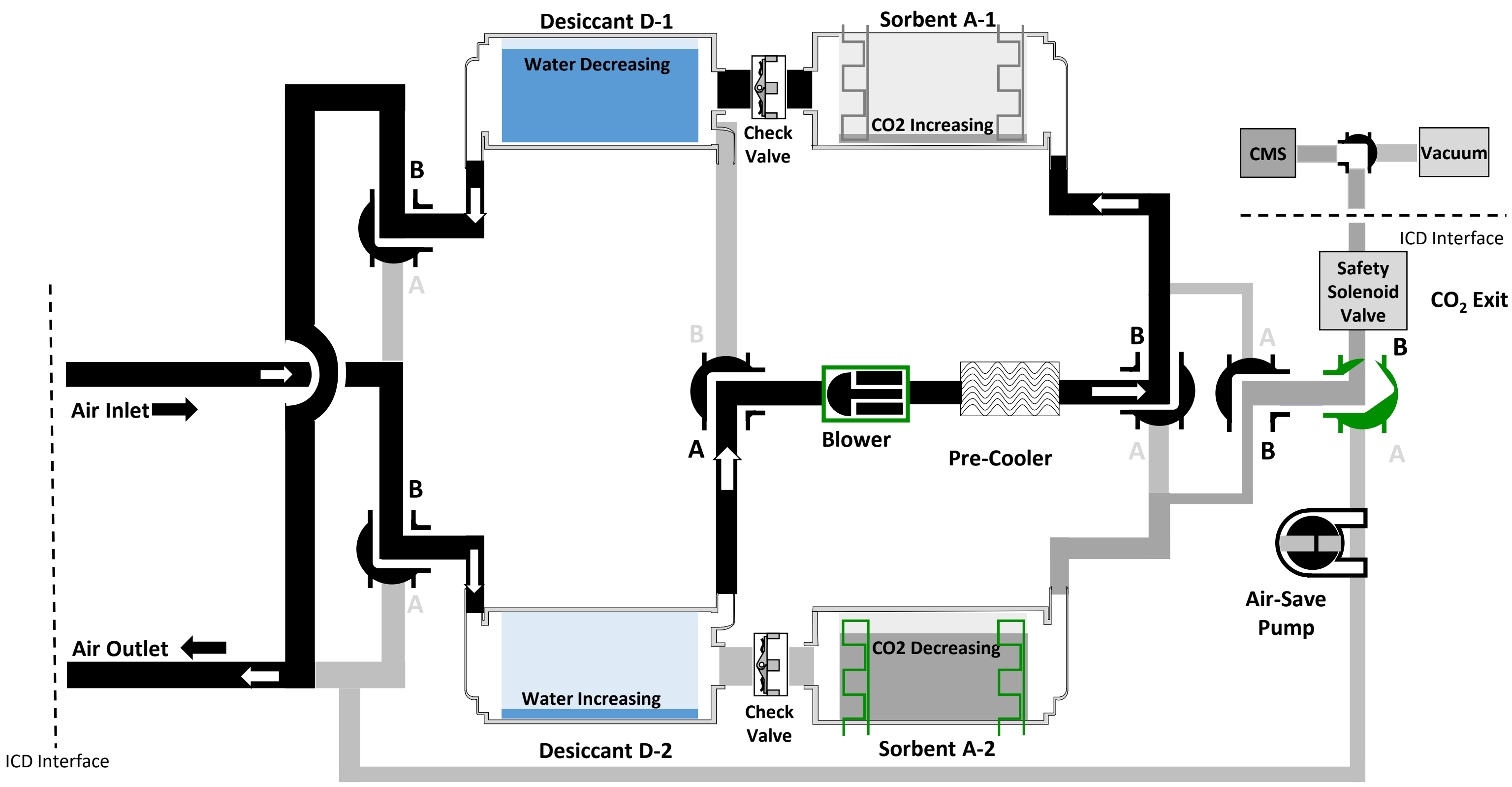


4BCO2 Operation (16)

Transition out of Second Half Cycle Air-Save

Half Cycle B

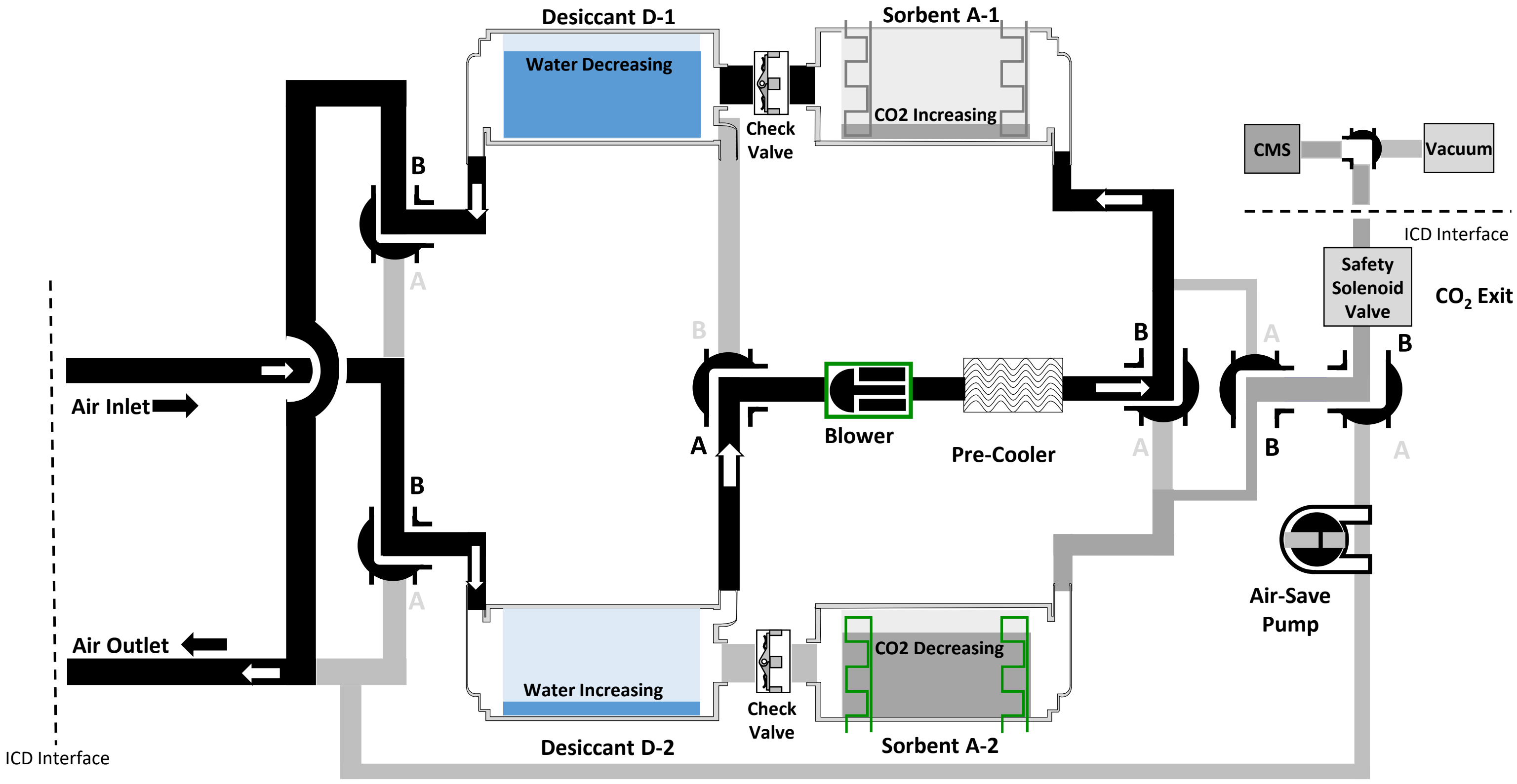
Segment B1, Mode 5



Adsorption of Bed A-1: Desorption of Bed A-2

Half Cycle B

Segment B2, Mode 6

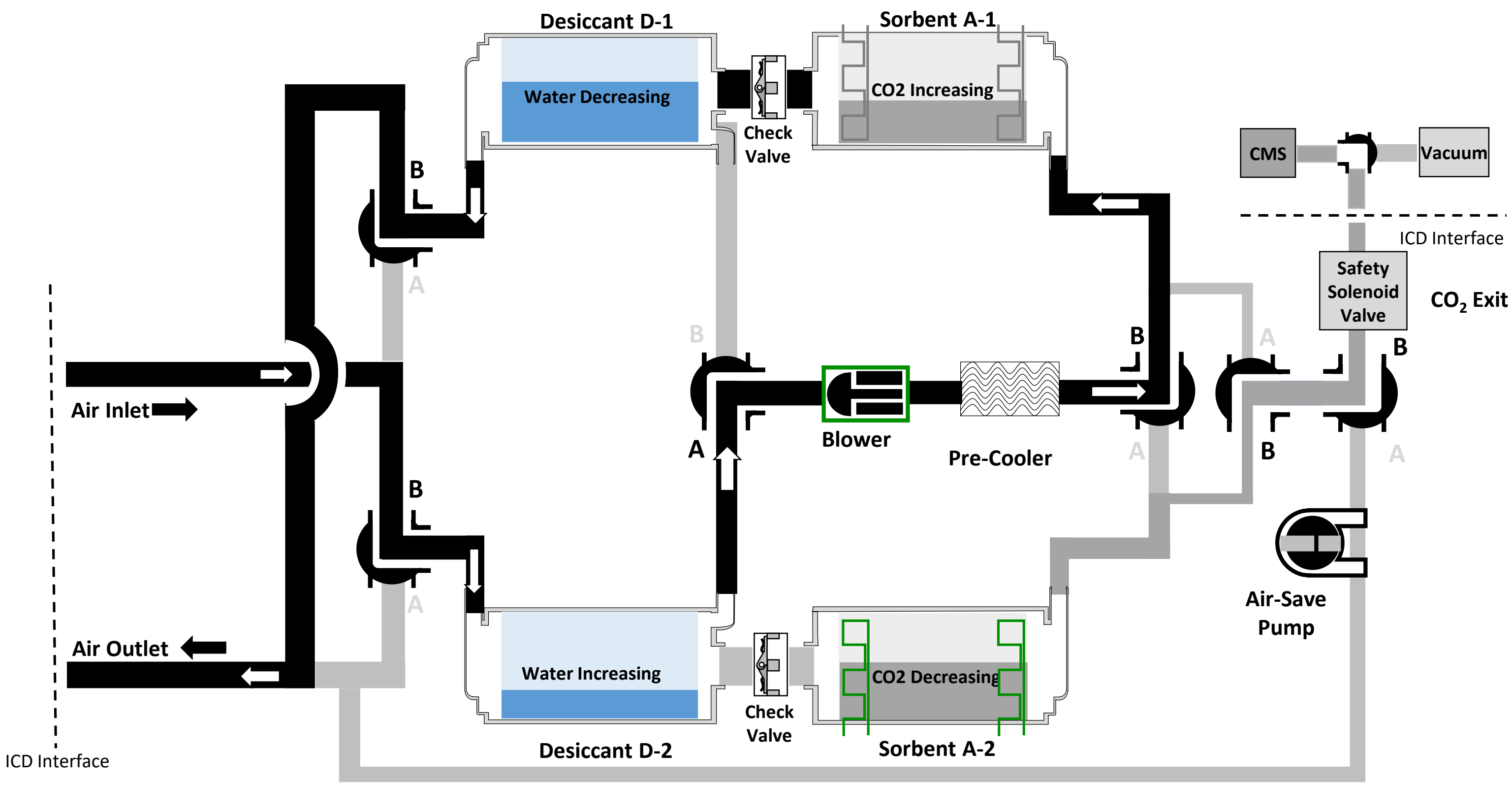


4BCO2 Operation (18)

Adsorption of Bed A-1: Desorption of Bed A-2

Half Cycle B

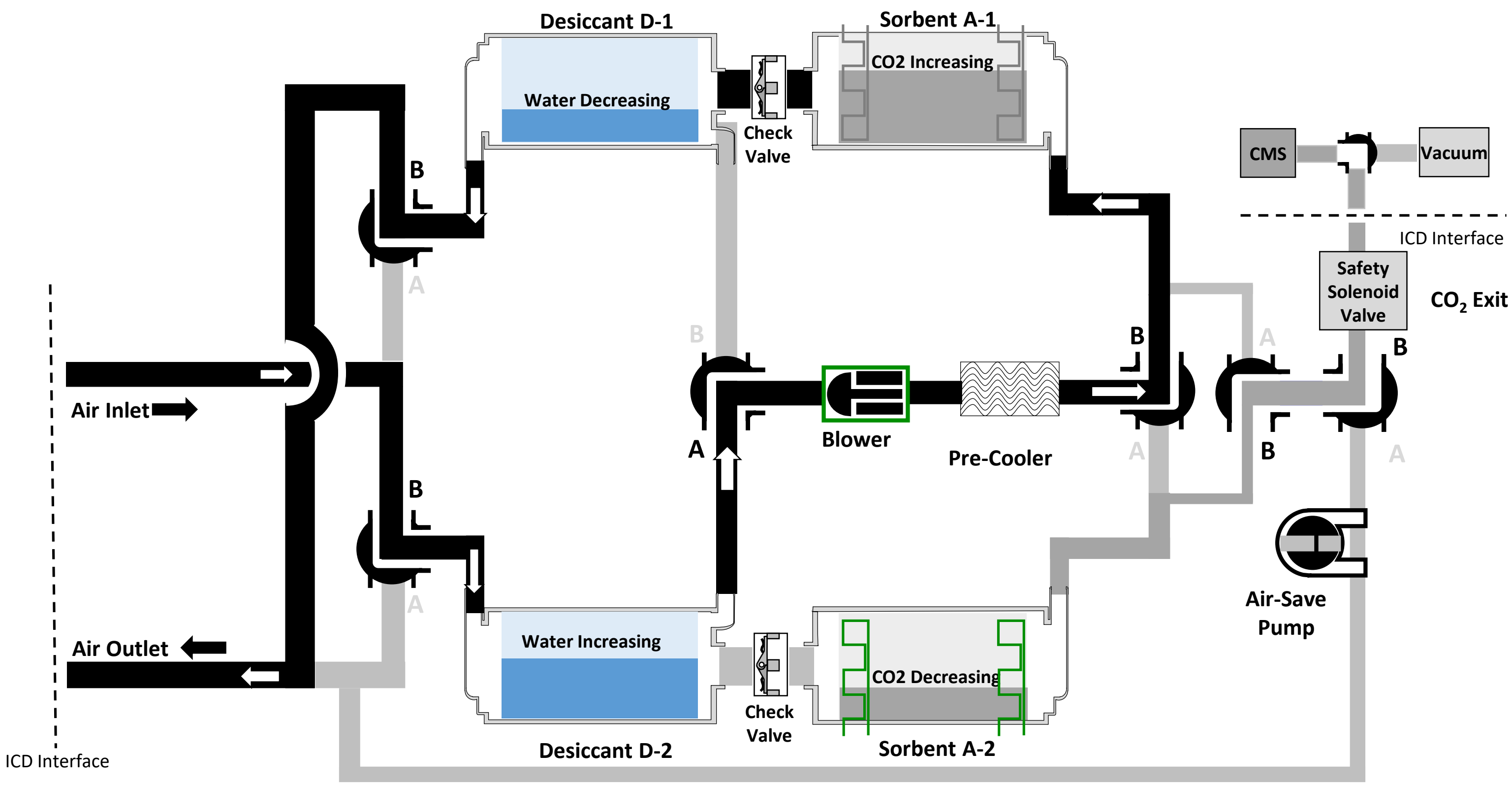
Segment B2, Mode 6



Adsorption of Bed A-1: Desorption of Bed A-2

Half Cycle B

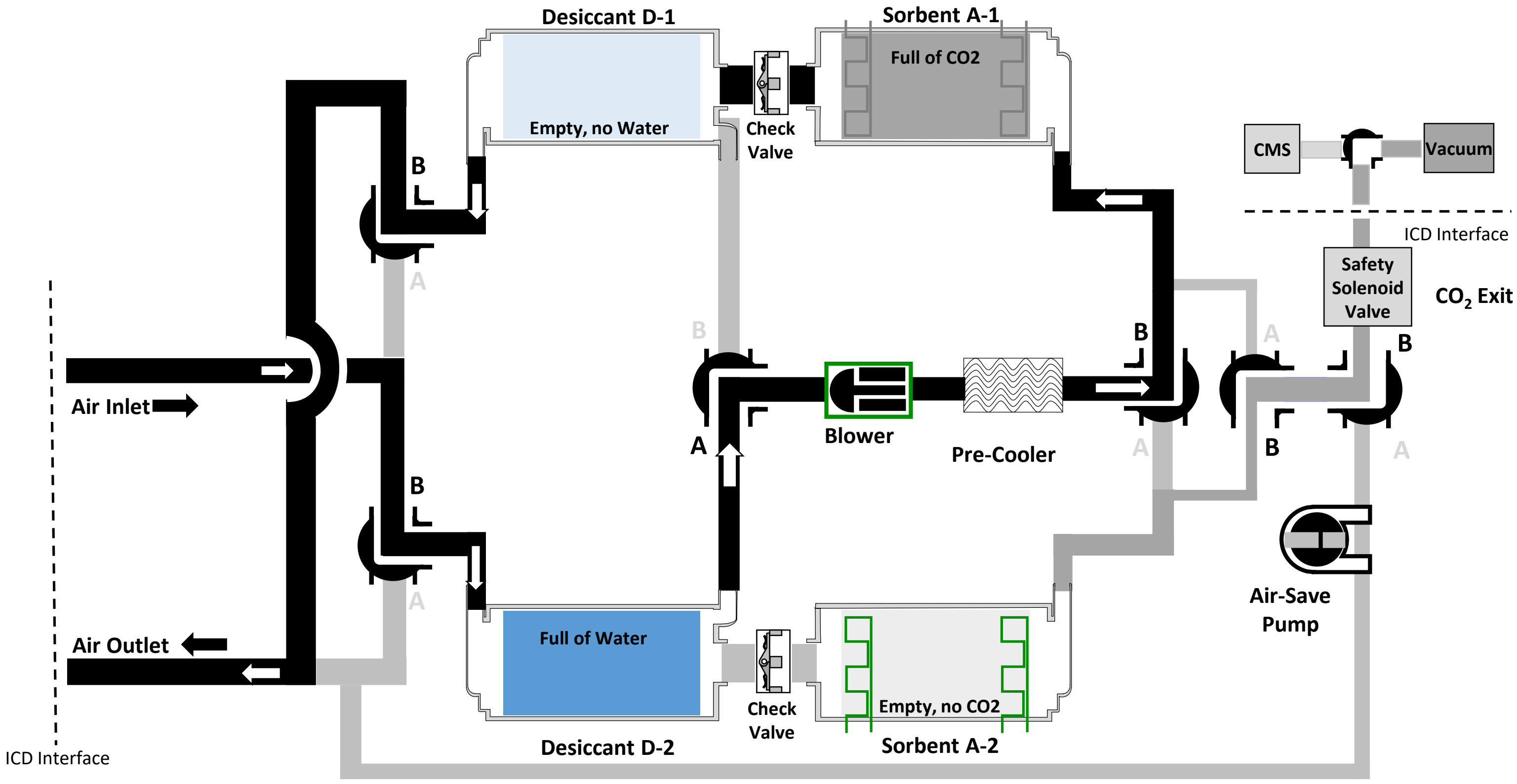
Segment B2, Mode 6



Vent to Vacuum

Half Cycle B

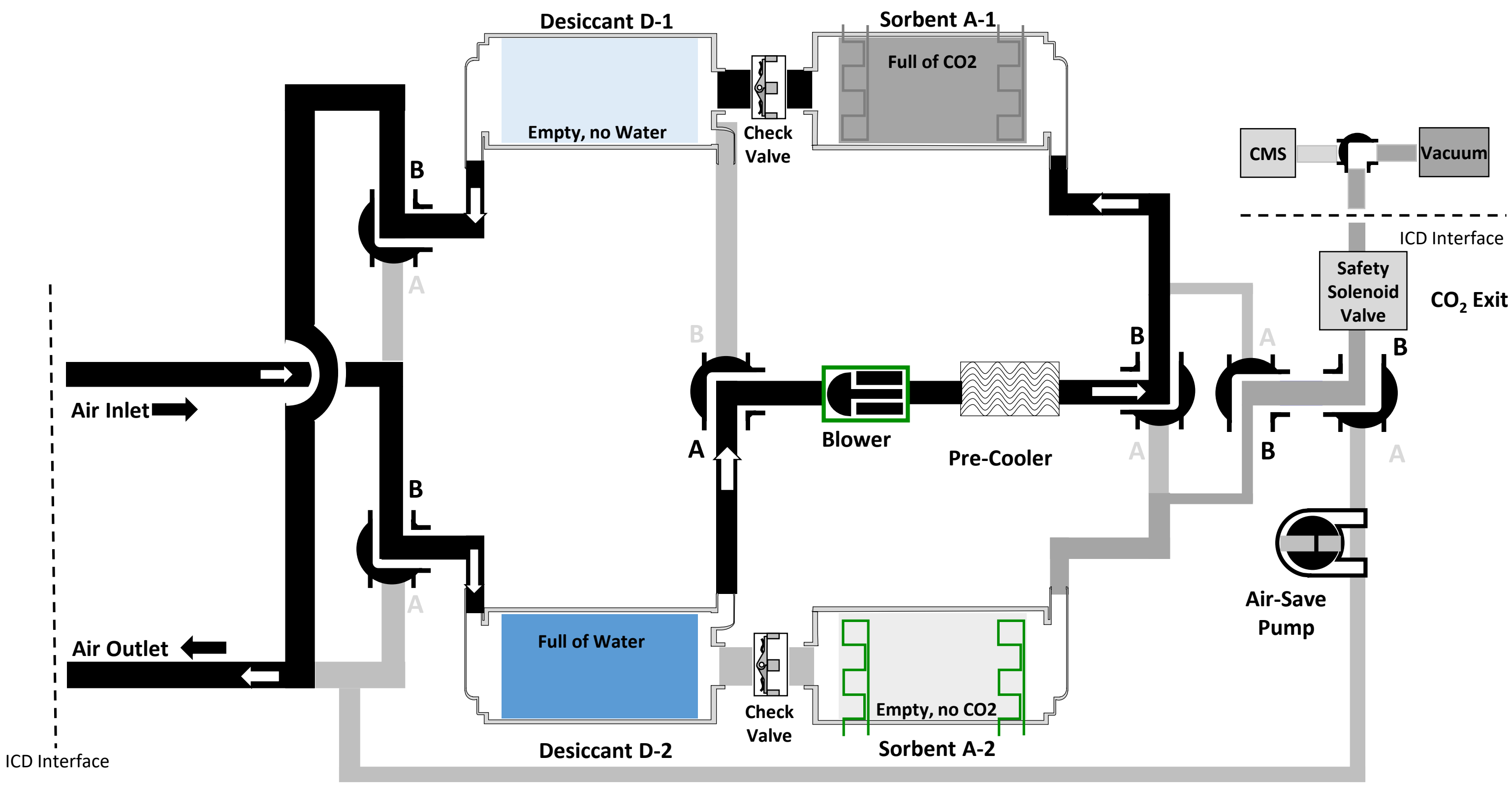
Segment B3, Mode 7



End of Second Half Cycle

Half Cycle B

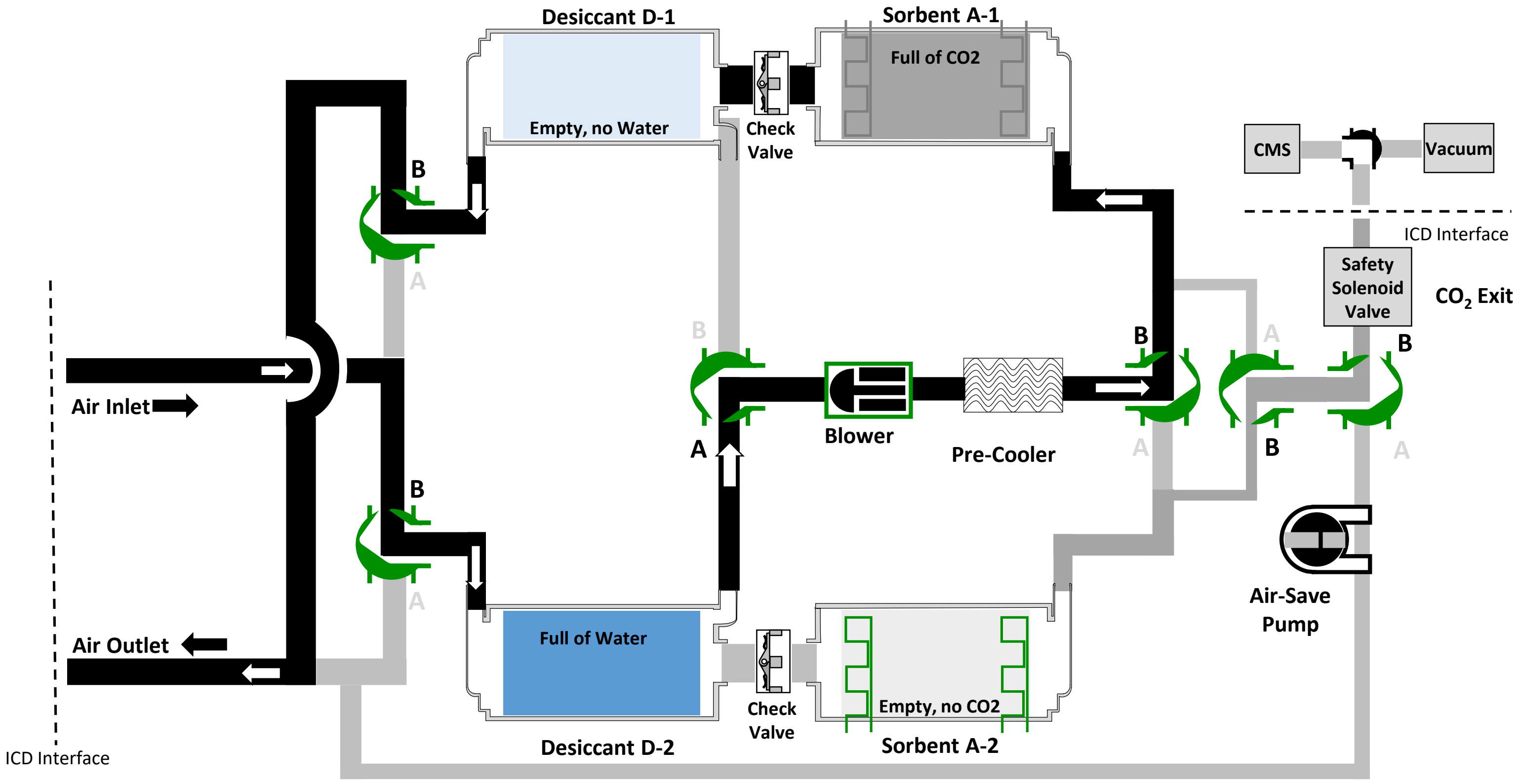
Segment B3, Mode 7



Transition to First Half Cycle

Half Cycle B

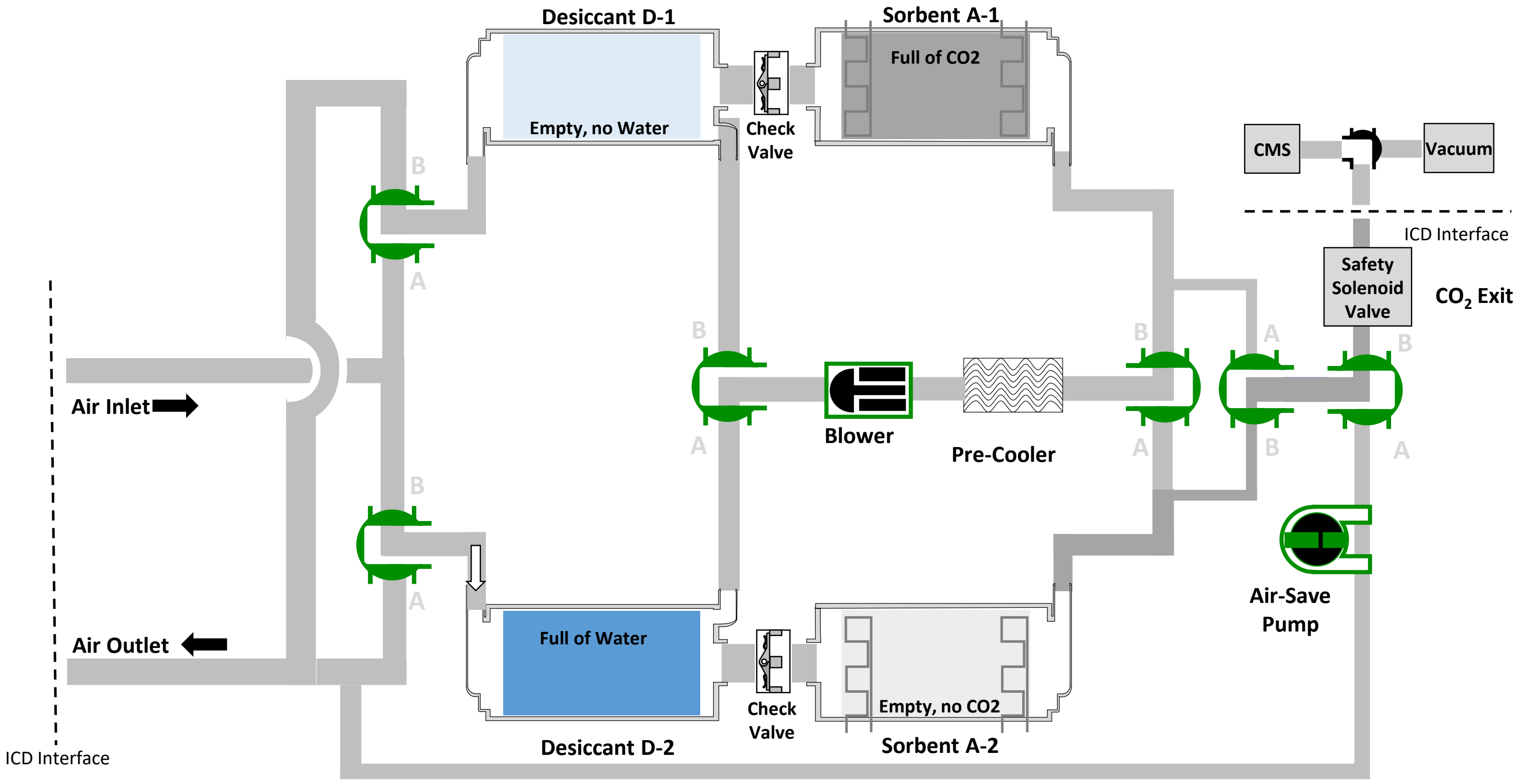
Segment B3, Mode 7



Transition to First Half Cycle

Temporary Cessation of All Air Flow

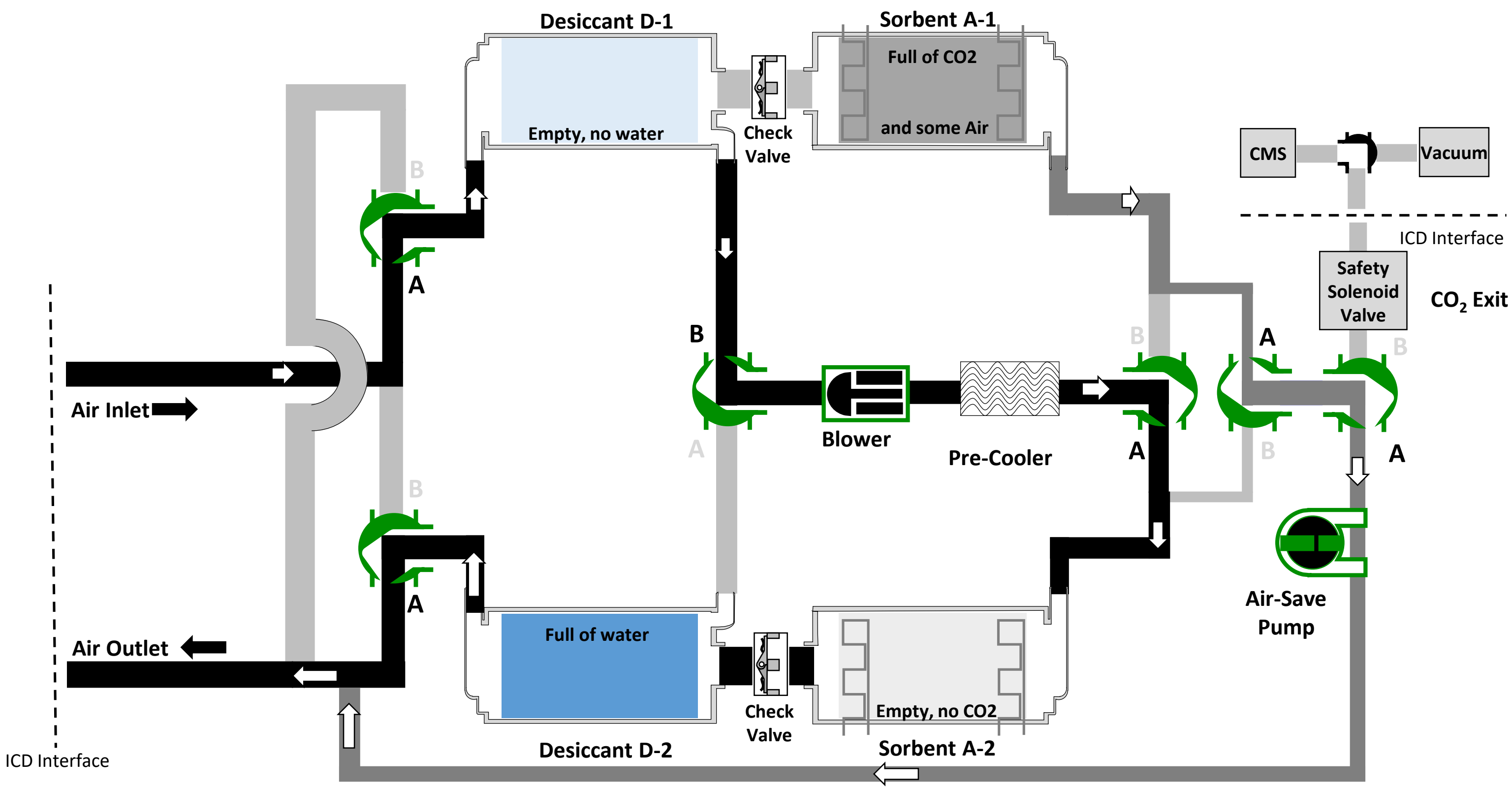
Segment B3, Mode 7



Transition to First Half Cycle

Half Cycle B

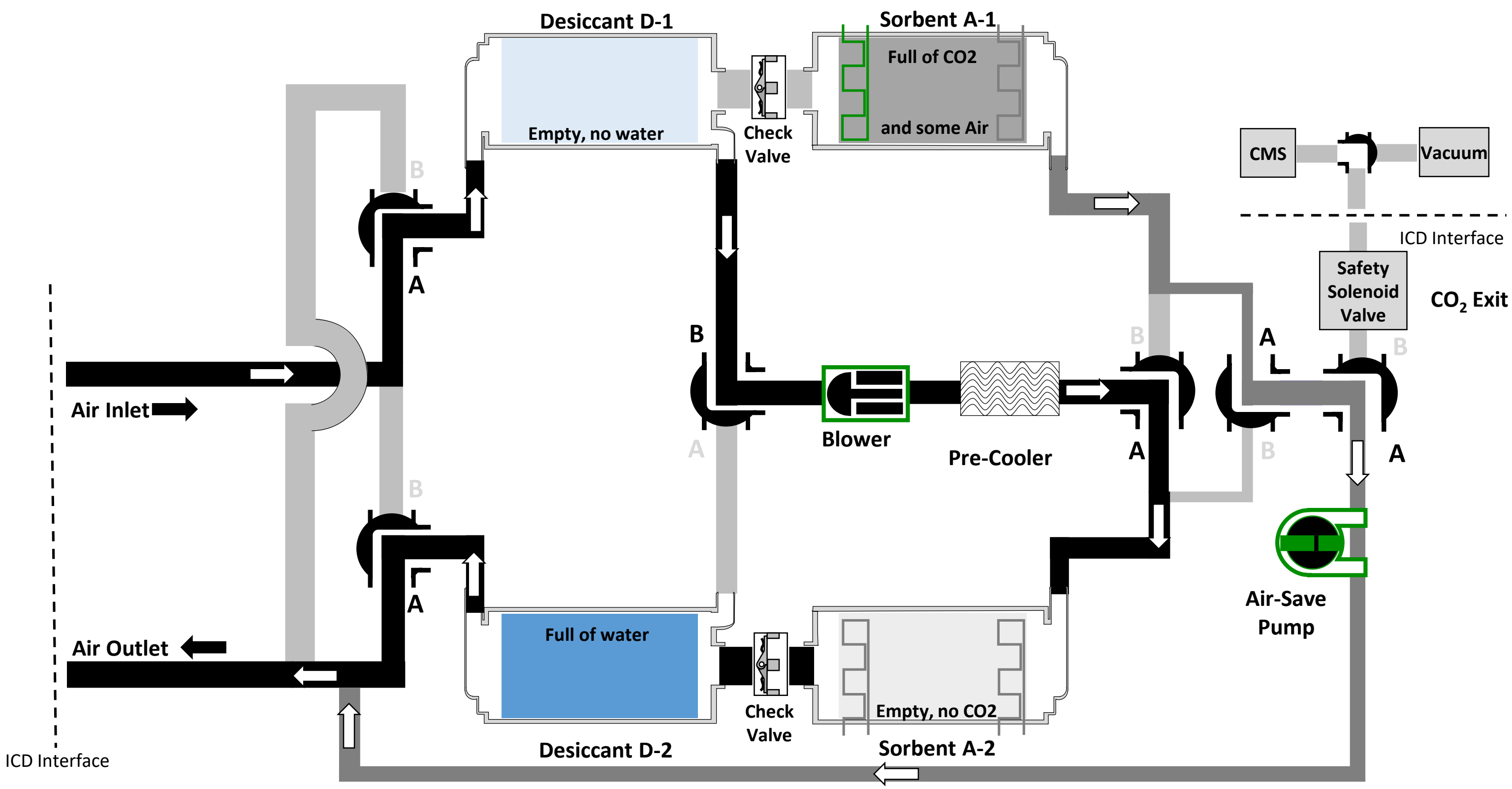
Segment B3, Mode 7



Air-Save

Half Cycle A

Segment A1, Mode 2



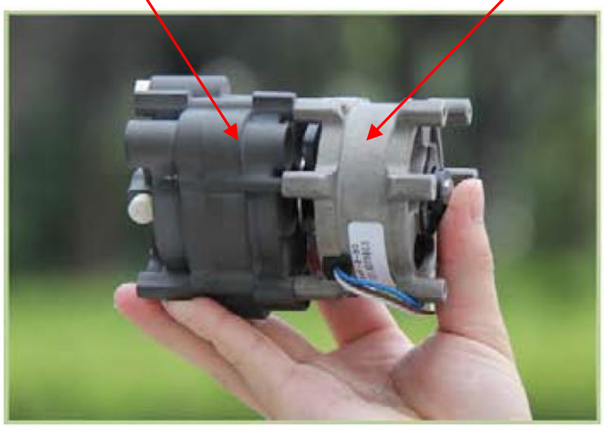
Repackaging the COTS Pump

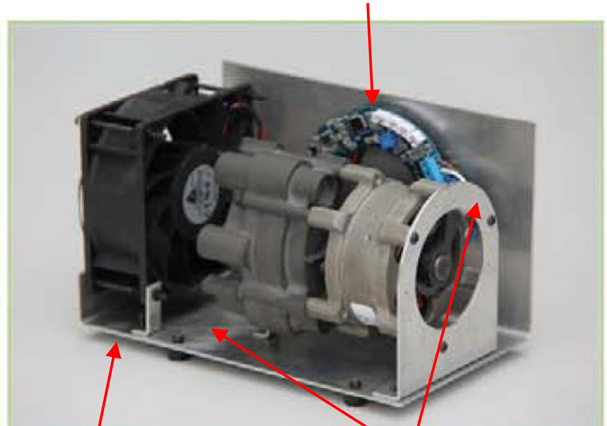
- Noise requirements drove repackaging the COTS pump and motor, putting it inside an acoustically insulated enclosure
  - Motor drive board relocated to separate avionics box
  - Motor and point mounted to LTL-cooled cold plate, no fan cooling

pump

motor

motor controller (moved)





fan (removed)

mounting structure (removed)

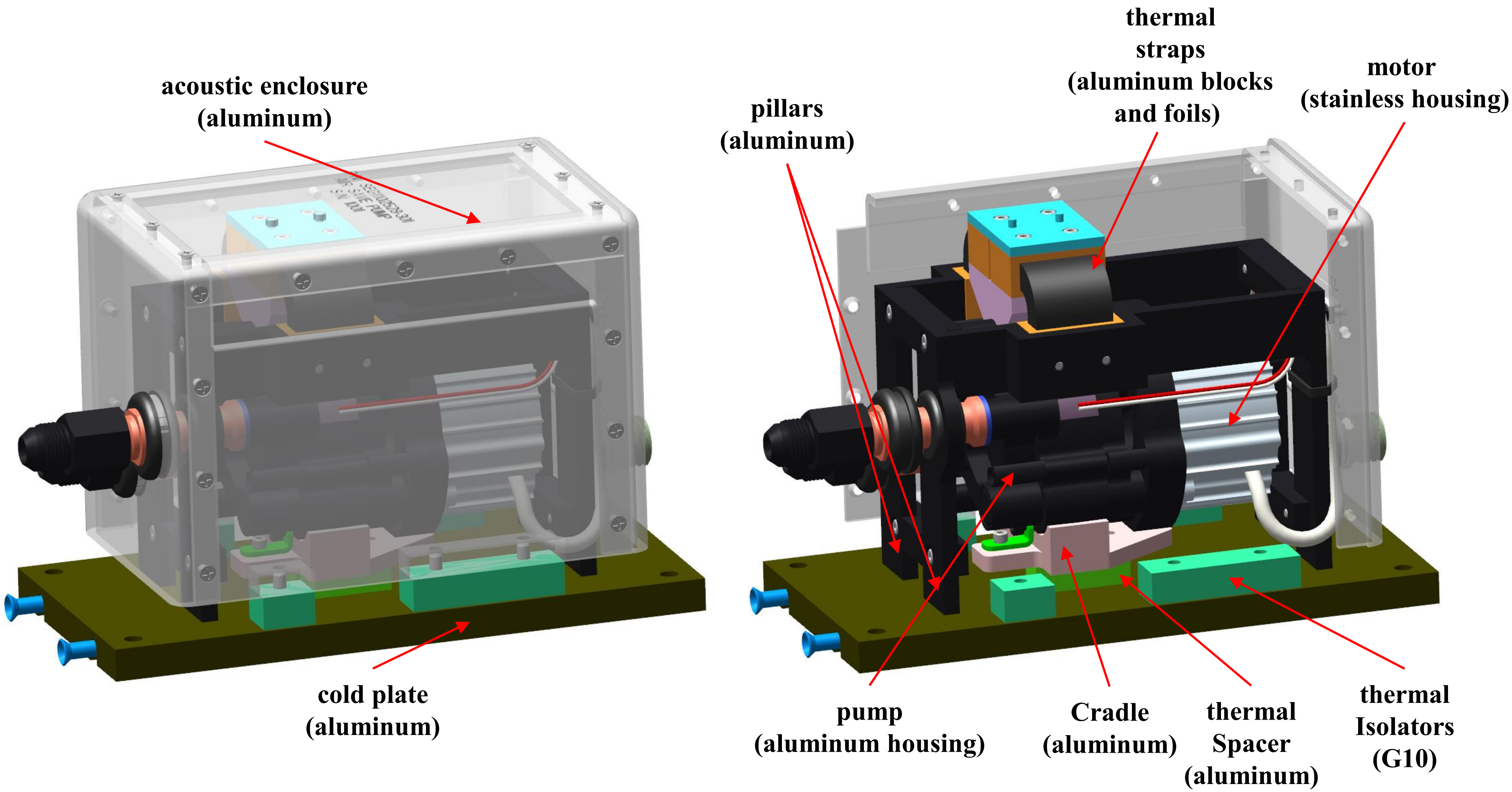
Thermal Limits

- **50C (122F) ambient rating in vendor-supplied form**
- **70C (158F) max pump housing**
- **65C (149F) max motor housing**

Performance characteristics

- **~75/25 pump/motor heat dissipation split**
- **Motor efficiency ~75%**
- **Pump efficiency = low (~4%) since pumping against deadhead vacuum most of the time**

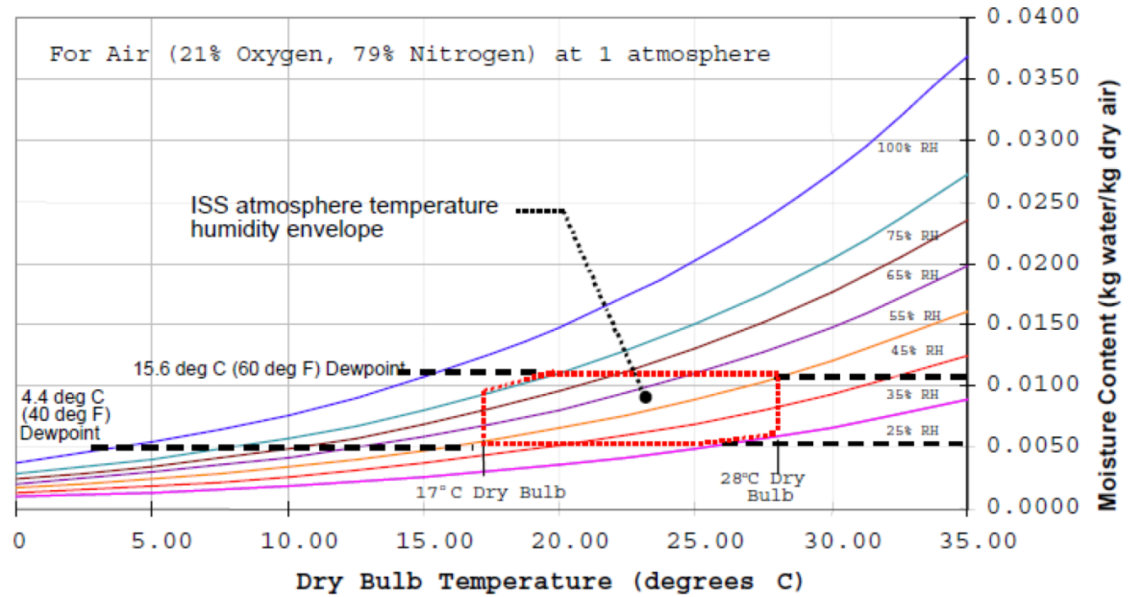
Repackaged Pump and Motor



Cold plate thermal insulation and acoustic insulation not shown

ISS Temperature/Humidity Envelope

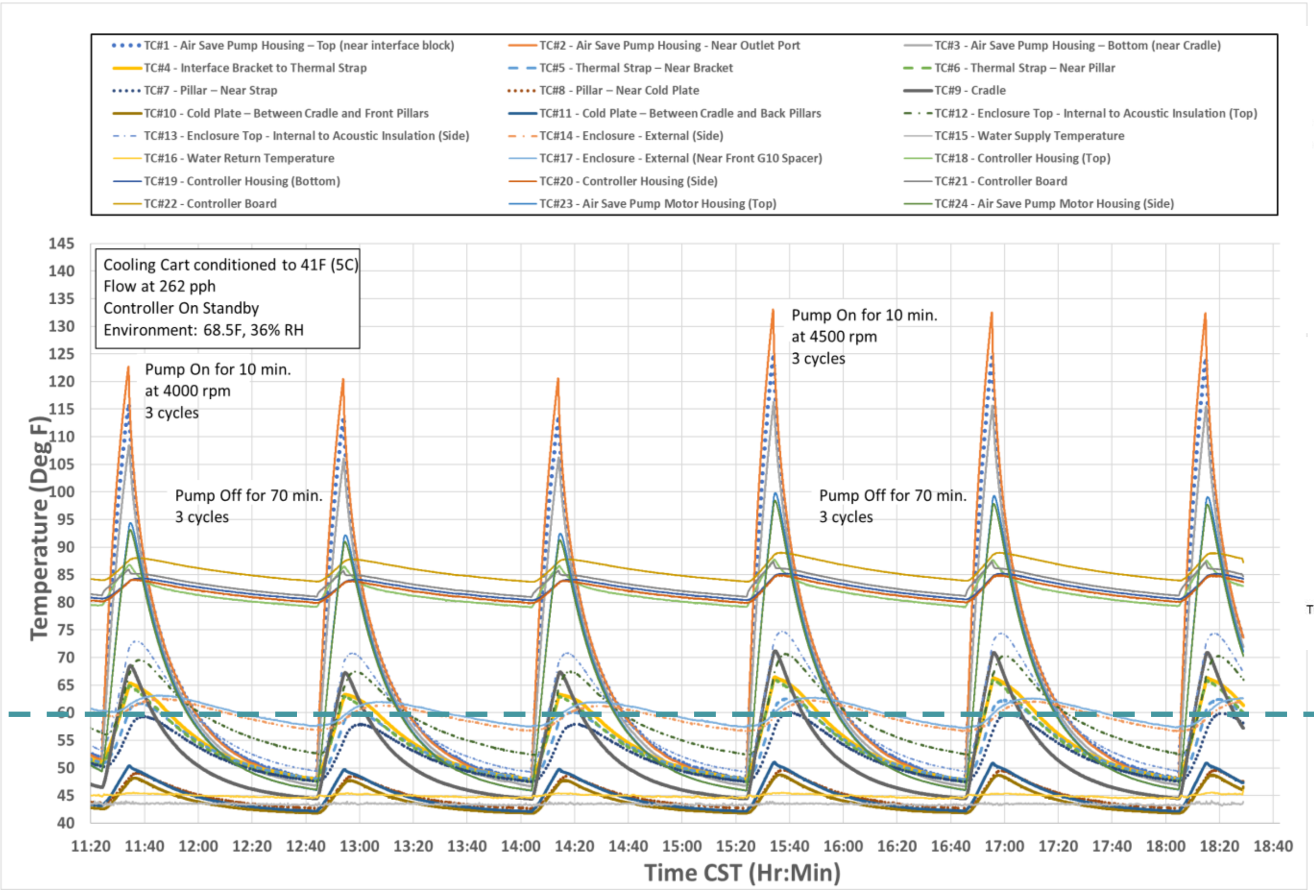
- SSP 57000 Rev S, Section 3.9.1 specifies condensation prevention requirements
  - Generally interpreted as avoiding surface temperatures below 15.6C (60F), the worst case cabin air dew point
  - Exceptions permitted if no fungus susceptibility
  - SSP 57000 ISS temperature/humidity environment applies to ISS cabin, but assumed to apply inside the 4BCO2 rack

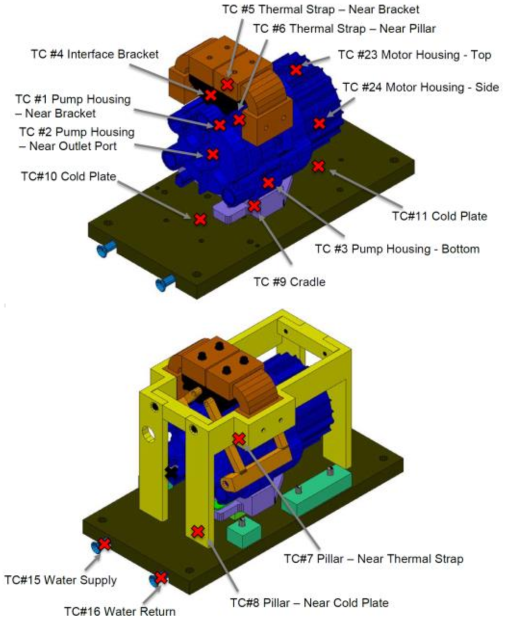


- Thermal characterization testing with the Flight Unit showed numerous temperatures below 15.6C (60F)

Flight Unit Thermal Characterization

- Thermal characterization testing with the Flight Unit showed numerous temperatures below 15.6C (60F)





Temperatures below 15.6C (60F)

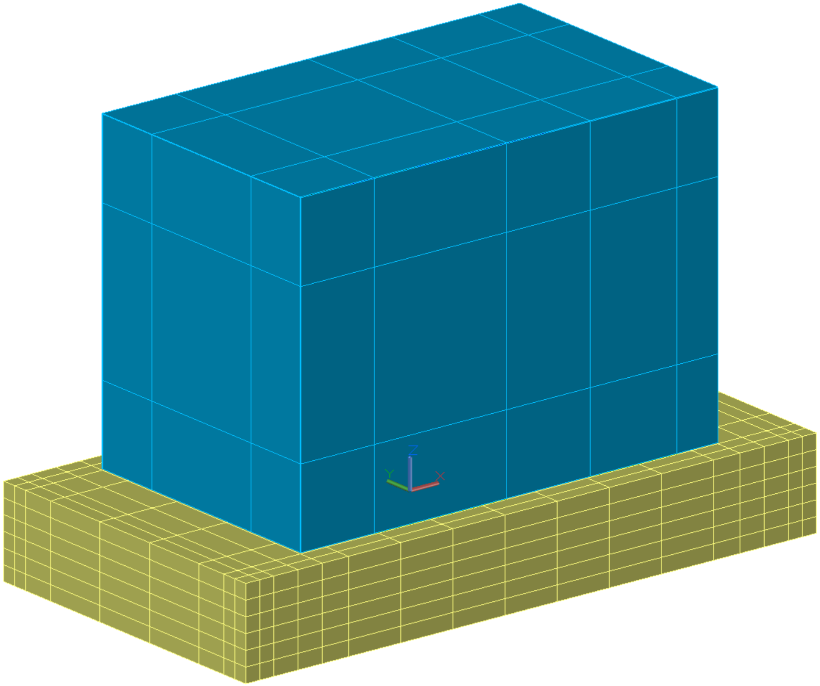
The Thermal Conundrum

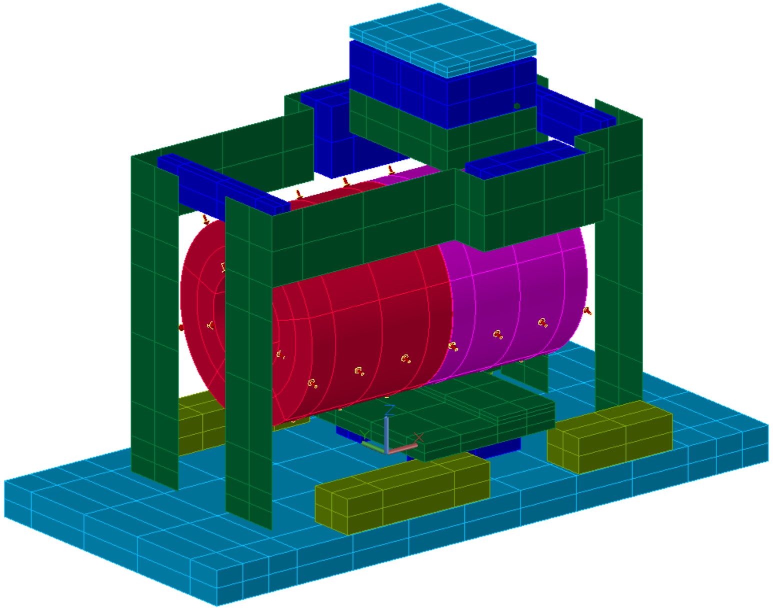
- In fan/air-cooled COTS configuration, possibility exists to treat pump as a simple “component” rated for 50C (122F) ambient conditions.
  - Ensuring rack air temperature less than 50C in vicinity of pump would suffice
  - Rack air < 100% relative humidity and pump temperature always ≥ rack air temperature ➔ no condensation
- Acoustic enclosure and cold plate results in need for thermal balance between competing goals
  - Pump and motor must not get too hot, BUT
  - Need to avoid over-cooling to prevent condensation
  - Acoustic enclosure precludes using avionics air to cool ASP
- LTL temperatures ranging from 3.3C (38F) to 10C (50F) pose a real condensation concern with 15.6C (60F) dew point limit
  - Low LTL temperatures required by pre-cooler performance demands

ASP Condensation Analysis

- ASP thermal model developed and run with Thermal Desktop (also part of 4BCO2 system level model)
- Model dialed-in to agree with transient thermal characterization test data for hot and cold cases.
- Resulting tuned thermal model used to identify design changes balancing and satisfying the competing thermal goals – *keeping pump and motor sufficiently cool without allowing condensation to form*
- Additional fluid model (Thermal Desktop FloCAD) predicted condensation formation and accumulation for a range of possible worst case conditions

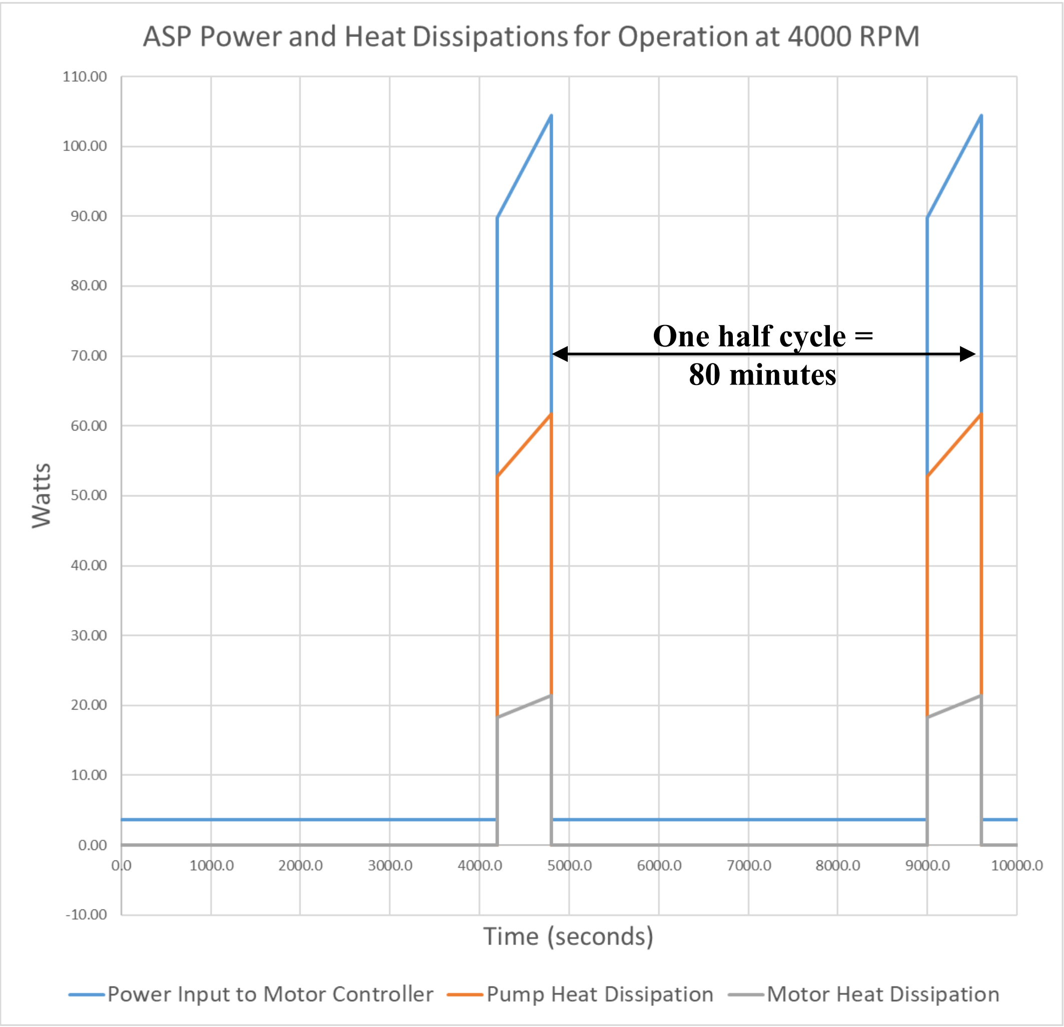
ASP Thermal Model





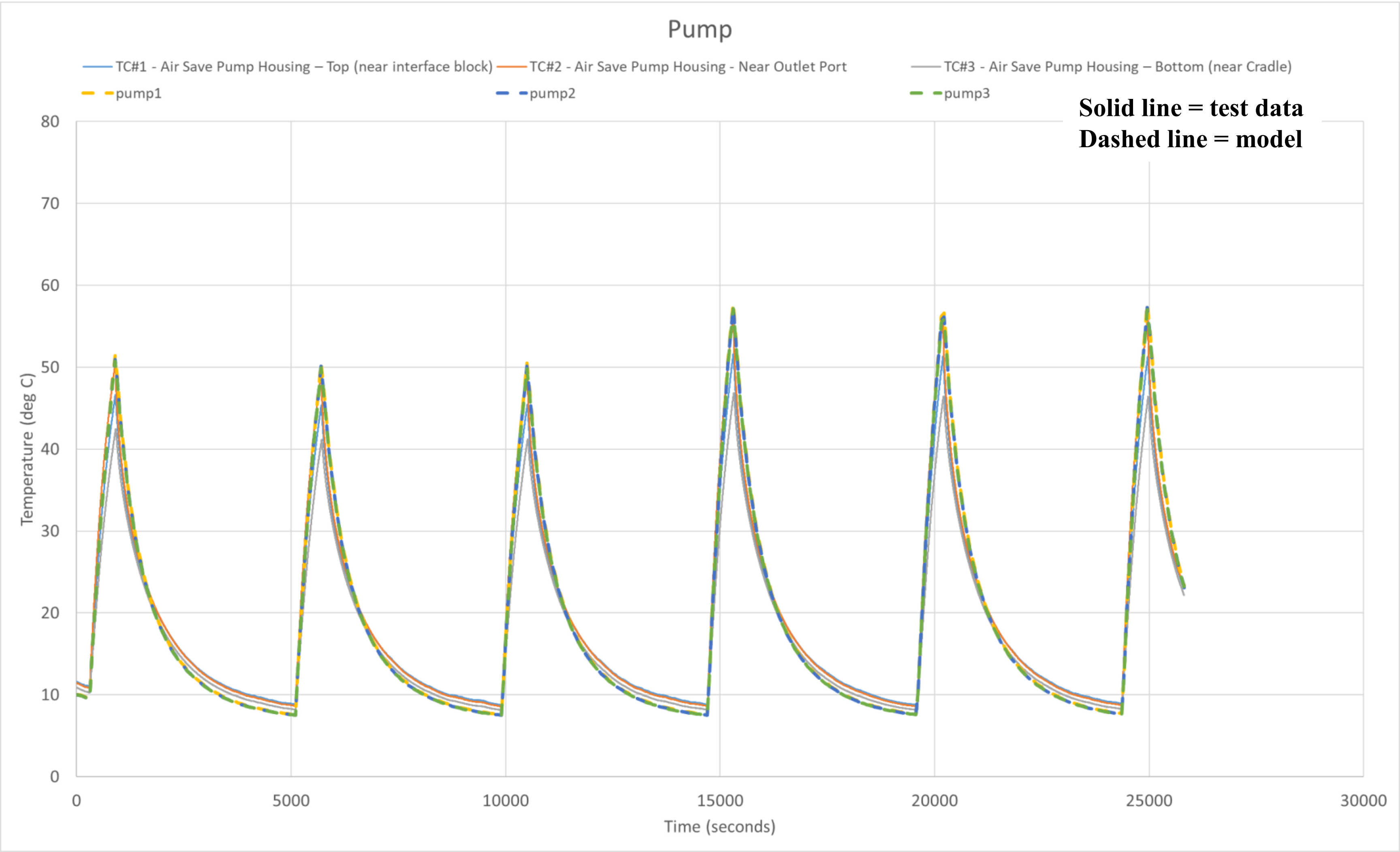
Cover and insulation removed

ASP Power and Heat Dissipation



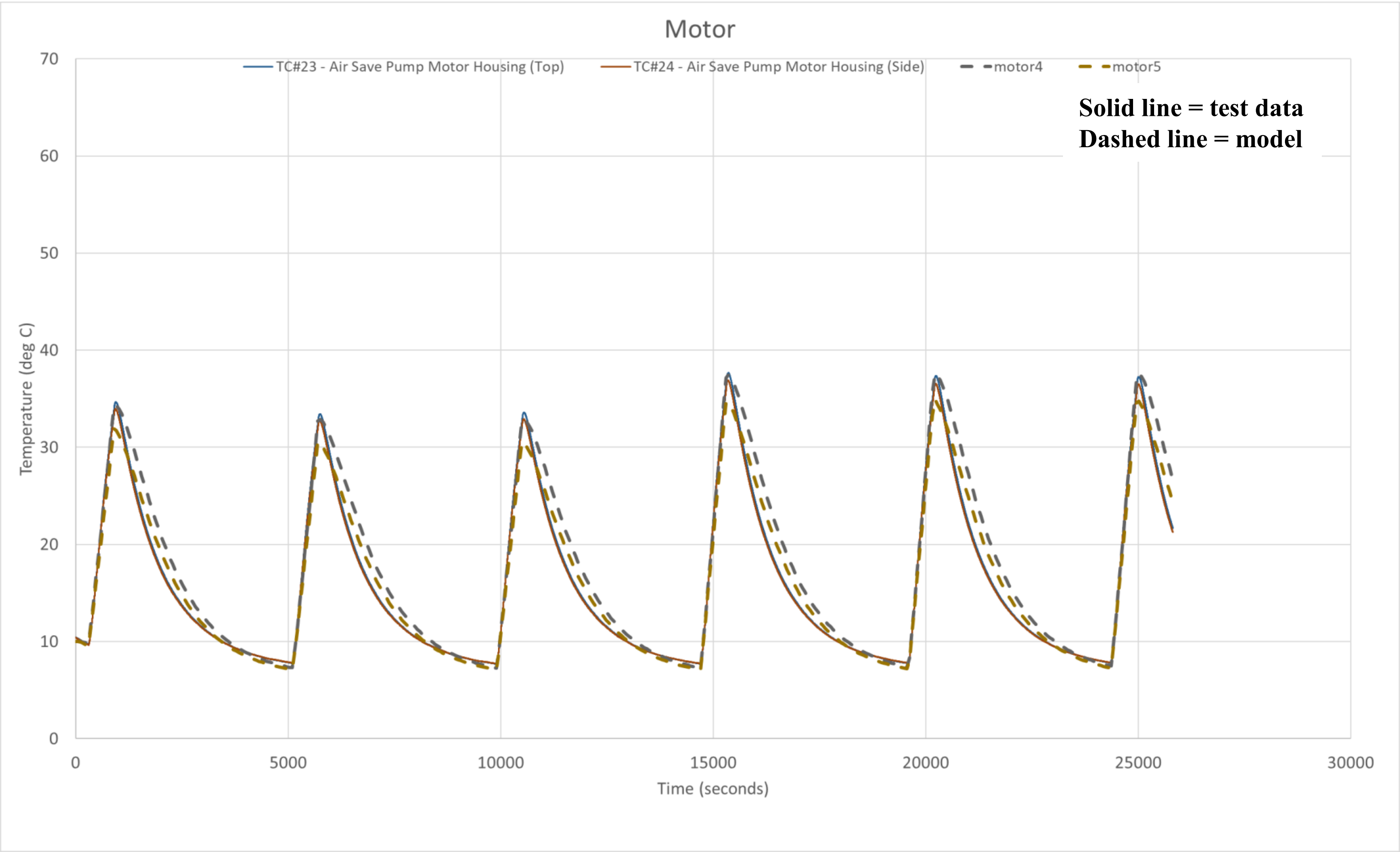
- Power measured at input to motor controller and used to compute pump and motor heat dissipation
- Assumptions
  - 3.6W controller standby power
  - 85% controller converter efficiency
  - 75% motor efficiency
  - 4% pump efficiency (averaged over 10 minute operation)
  - Linear power variation over 10 minute pump down (higher power when pumping against dead head vacuum

Model Calibrated to Test: Pump



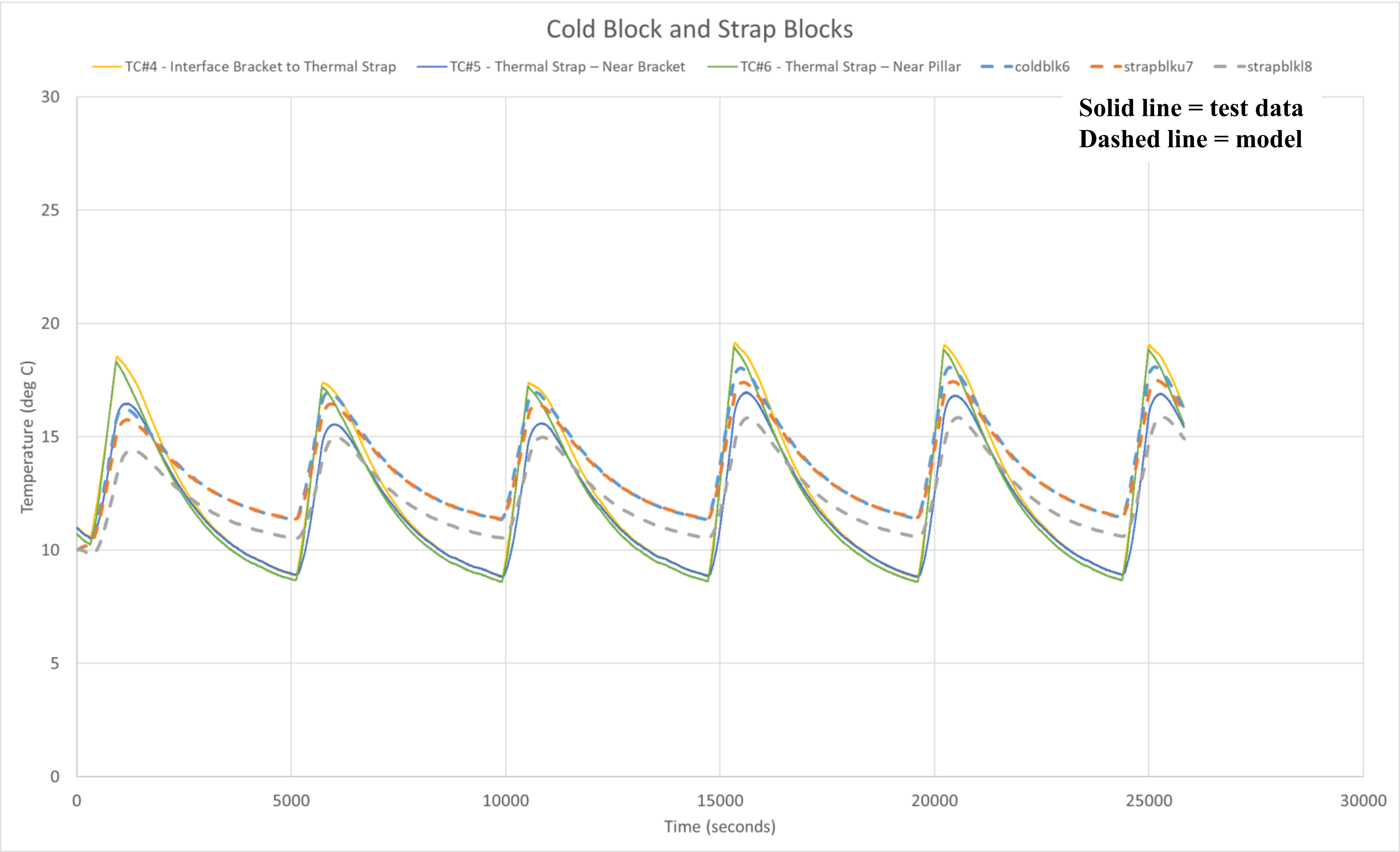
Only cold test shown, similar model-to-test agreement seen for hot test

Model Calibrated to Test: Motor



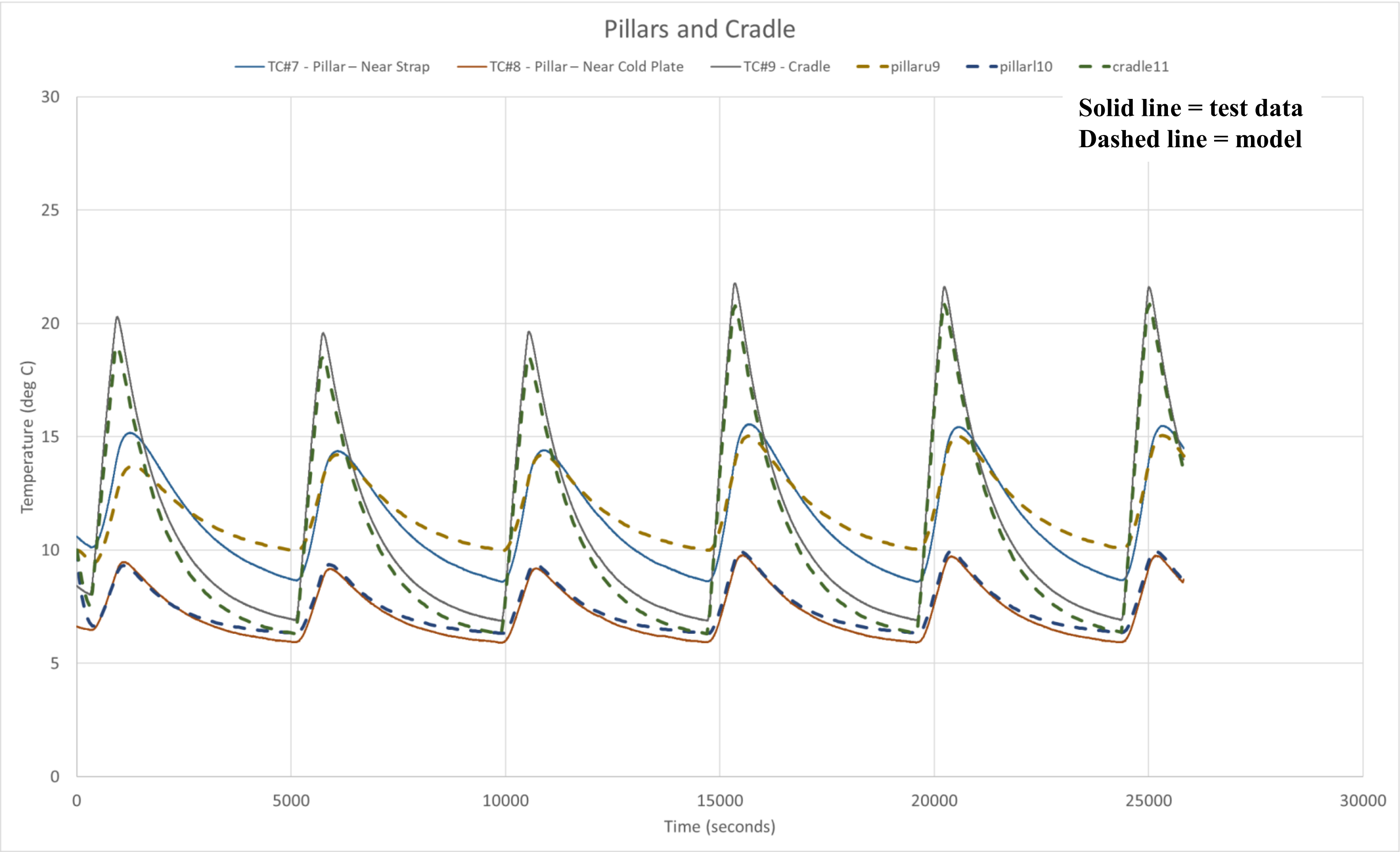
Only cold test shown, similar model-to-test agreement seen for hot test

Model Calibrated to Test: Cold Block and Strap Blocks



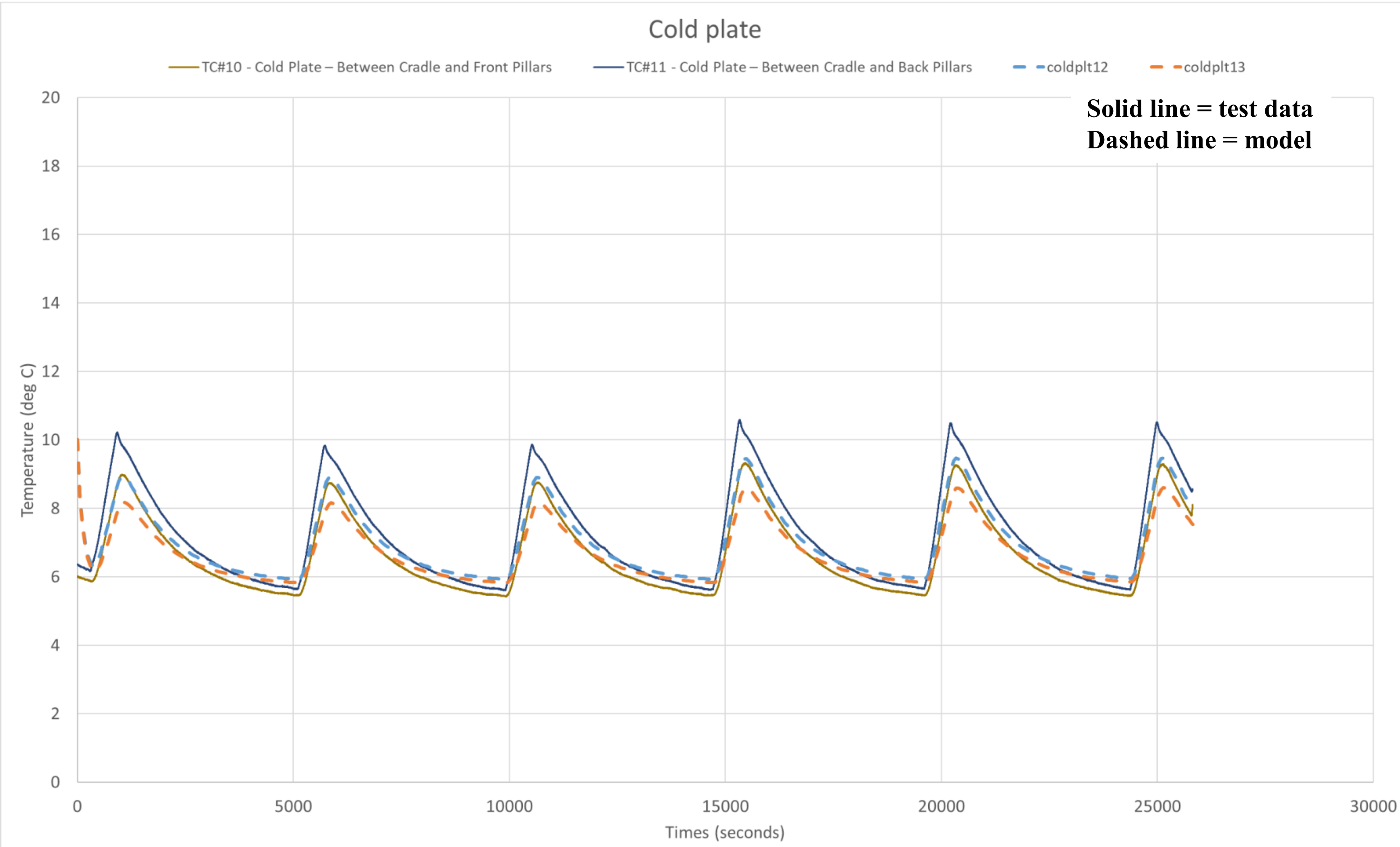
Only cold test shown, similar model-to-test agreement seen for hot test

Model Calibrated to Test: Pillar and Cradle



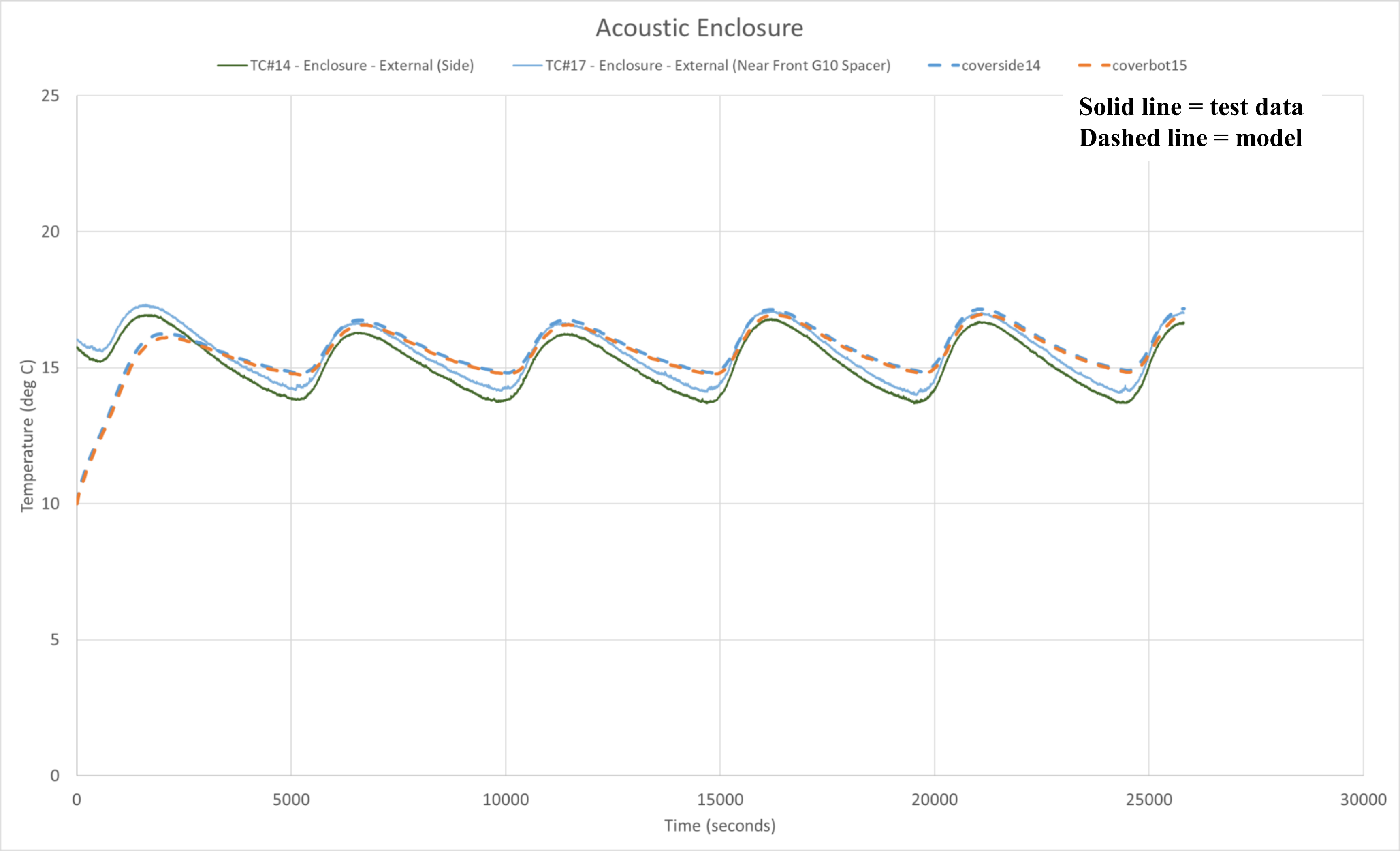
Only cold test shown, similar model-to-test agreement seen for hot test

Model Calibrated to Test: Cold Plate



Only cold test shown, similar model-to-test agreement seen for hot test

Model Calibrated to Test: Acoustic Enclosure



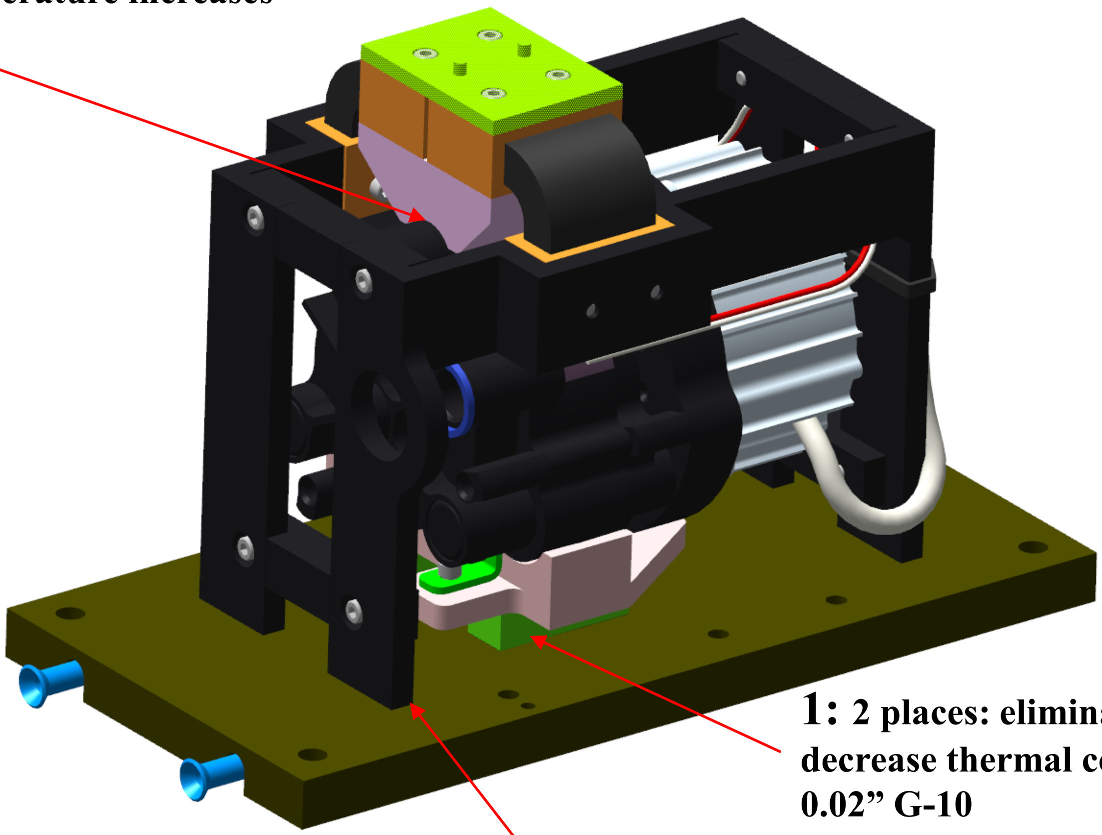
Only cold test shown, similar model-to-test agreement seen for hot test

Thermal Design Study

- Using the dialed-in thermal model …
- Cases based on conditions predicted in the rack:
  - Cold case – try to get temperatures > 15.6C (60F)
  - Hot case – make sure pump temperature < 70C (158F) and motor temperature < 65C (149F)
- Analysis predicted no exterior condensation for expected cold operating conditions
- Found these design mods
  - Decrease thermal coupling to the cold plate by eliminating indium shims in lieu of thermal insulator shims
    - Supports beneath cradle
    - Beneath legs of pillars
  - Increase thermal coupling from pump to upper cold block to offset pump and motor temperature increases caused by the thermal insulator shims

ASP Design Changes

3: Improve thermal coupling to offset pump and motor temperature increases caused by 1 & 2



1: 2 places: eliminate indium shim, decrease thermal coupling to equivalent 0.02” G-10

2: 4 places: eliminate indium shims, decrease thermal coupling to equivalent 0.04” G-10

Design Outcome

- Project decided not to modify the first flight unit, though these changes could be applied to the second flight unit
  - Late in project schedule
  - Decided to accept condensation risk on basis of fungus resistant materials used throughout
- Still need to look at condensation risk
  - Necessity of on-orbit condensation mitigation steps?
    - Inspection?
  - Motor not design for operation in presence of liquid water, wiring not hermetically sealed to housing
    - Motor OK for high humidity noncondensing conditions
    - Pump OK in presence of condensatio

Condensation Fluid (FloCAD) Model

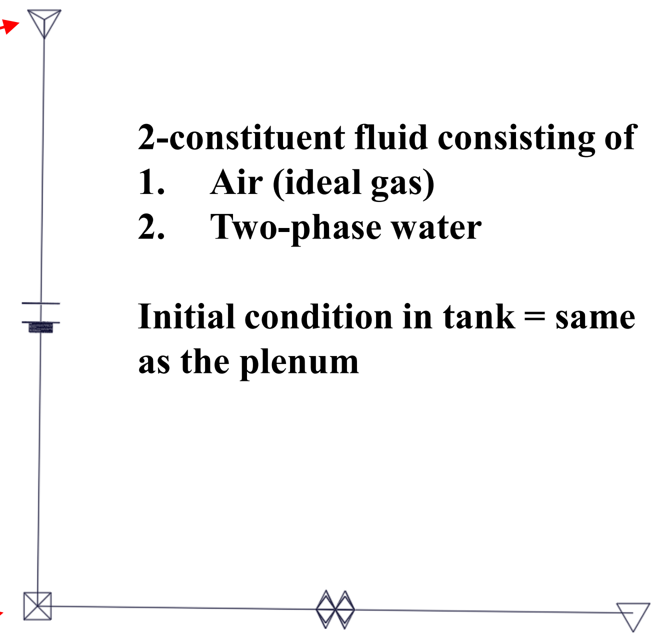
Plenum at 29.4C (85F), 2 humidity conditions

1. 15.6C (60F) dew point = 43% relative humidity – nominal worst case
2. 75% relative humidity (24.5C = 76.1F dew point) – extreme worst case

2-constituent fluid consisting of

1. Air (ideal gas)
2. Two-phase water

Initial condition in tank = same as the plenum



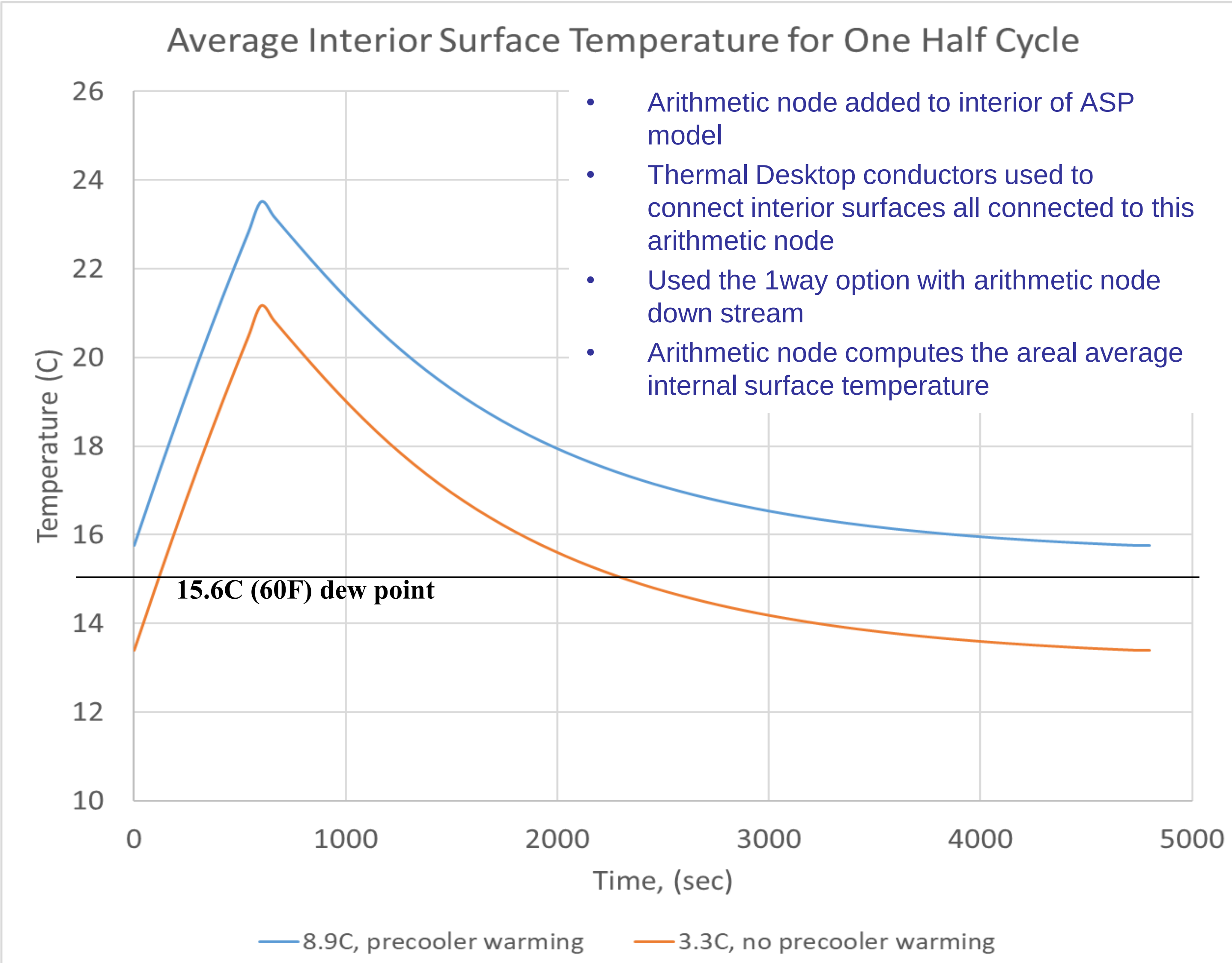
Orifice
Represents air leak path into the enclosure
Phase specific suction – only water vapor allowed to pass, trapping liquid water in the enclosure

Tank
80 in^3 volume

Fluid tie, based on 353 in^2 surface area, and 1 inch thick conduction path through air

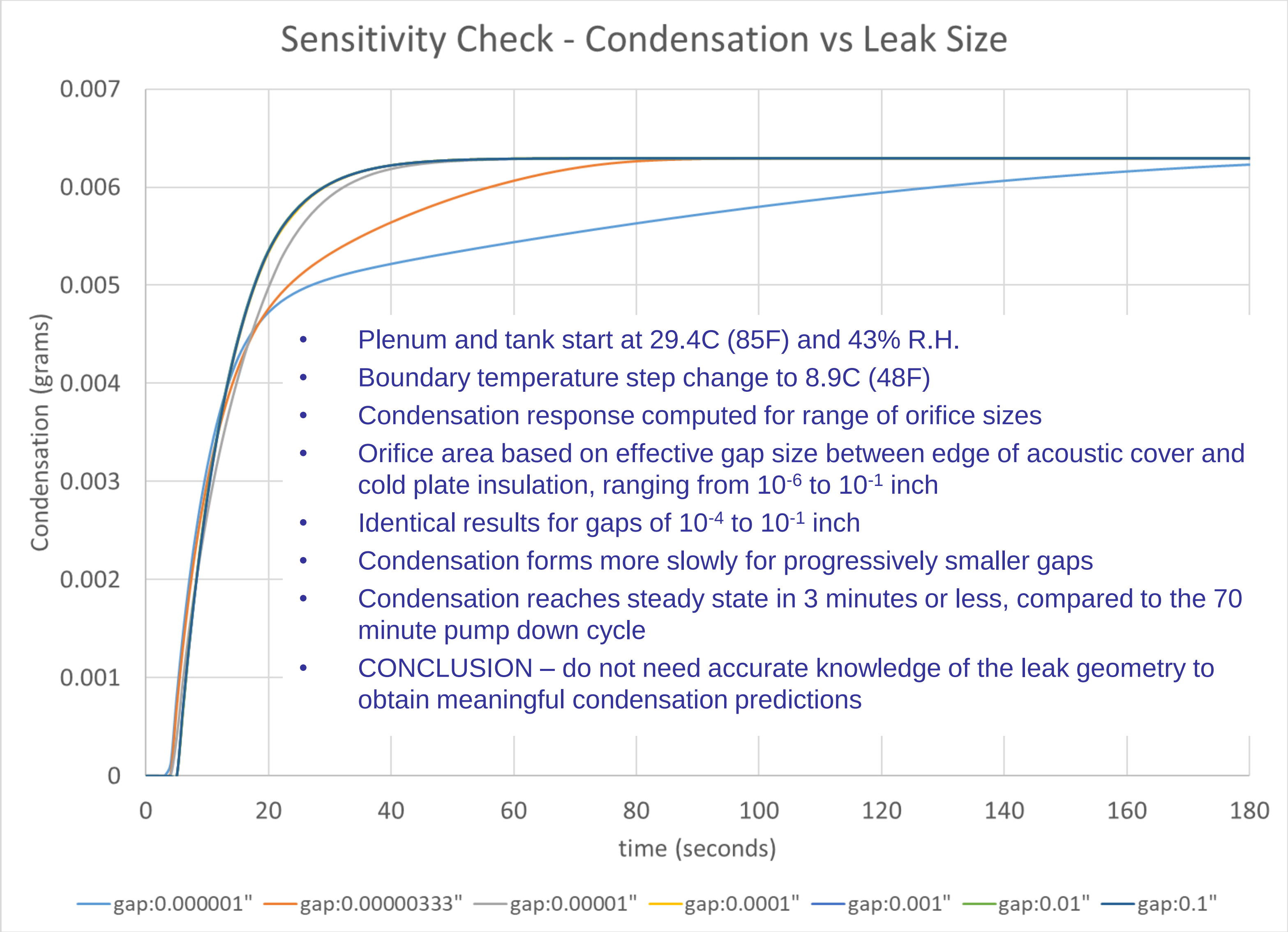
Thermal boundary node: time dependent temperature derived from ASP thermal model

Average Interior Surface Temperature



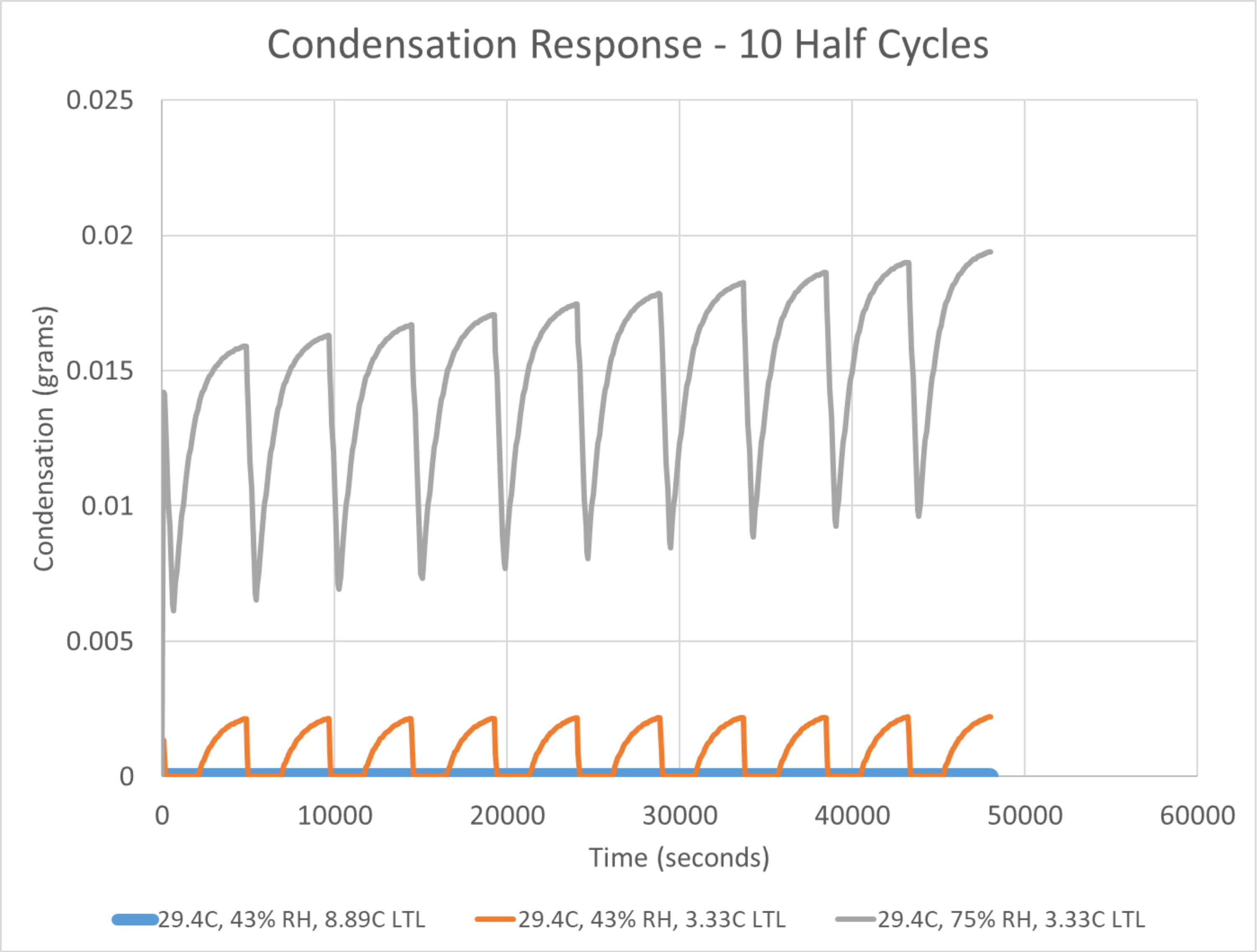
- Arithmetic node added to interior of ASP model
- Thermal Desktop conductors used to connect interior surfaces all connected to this arithmetic node
- Used the 1way option with arithmetic node down stream
- Arithmetic node computes the areal average internal surface temperature

Leak Size Sensitivity Study

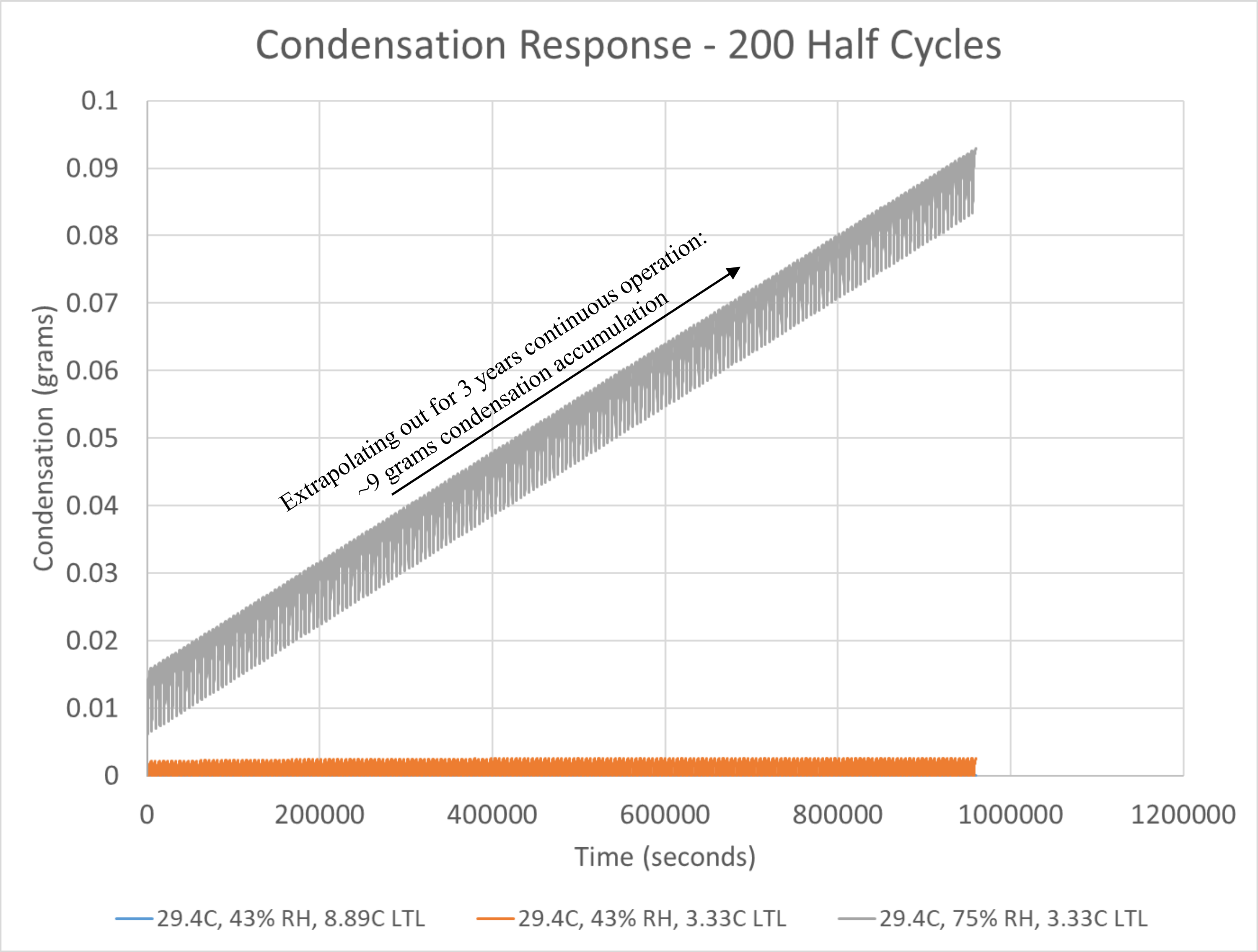


- Plenum and tank start at 29.4C (85F) and 43% R.H.
- Boundary temperature step change to 8.9C (48F)
- Condensation response computed for range of orifice sizes
- Orifice area based on effective gap size between edge of acoustic cover and cold plate insulation, ranging from 10^{-6} to 10^{-1} inch
- Identical results for gaps of 10^{-4} to 10^{-1} inch
- Condensation forms more slowly for progressively smaller gaps
- Condensation reaches steady state in 3 minutes or less, compared to the 70 minute pump down cycle
- CONCLUSION – do not need accurate knowledge of the leak geometry to obtain meaningful condensation predictions

Condensation Prediction



Condensation Prediction



Condensation Predictions

- Ran cyclic simulation with average surface temperature obtained from ASP thermal model

Plenum and Initial Condition	Inlet temperature to ASP cold plate	Comment	Result
29.4C (85F), 43% R.H.	8.9C (48F) – includes precooler warming effect	Reasonable worst case	No condensation
29.4C (85F), 43% R.H.	3.3C (38F) – excludes precooler warming effect	Moderately extreme worst case	Condensation forms on each half cycle, but completely evaporates … no accumulation
29.4C (85F), 75% R.H.	3.3C (38F) – excludes precooler warming effect	Extreme worst case	Condensation forms on each half cycle, but does not completely evaporate … condensation accumulates. Assume 3 year mission running continuously at these extreme worst case conditions, ~9 mL predicted to form

- CONCLUSION: condensation unlikely to form, condensation risk of flying as-is design falls between zero and very small

References

- 4BCO2-DOC-003A Four Bed CO2 Scrubber Concept of Operations
- 4BCO2-RQMT-004D System Requirements and Verifiaiton Matrix
- ISS Pressurized Payloads Interface Requirements Document, SSP 57000 Rev S
- Air Save Pump Assembly and Controller Thermal Characterization Test for Flight Unit, JETS-JE33-20-TLSS-TP-0012, 2/27/2020
- Thermal Desktop (Version 6.0) technical documentation
- Scroll Labs Datasheet and User Guide for SVF-50 Miniature Dry Floating Scroll Vacuum Pump

- Acknowledgement to Warren Peters (MSFC-ES62) who created the 4BCO2 cycle diagrams and pseudo animation

Questions?